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AMS Tracker Thermal Control Subsystem
TTCS Safety Approach

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Document change log

Change Ref.	Section(s)	Issue 1.0
-	All	Initial issue
Change Ref.	*Section(s)*	*Issue 1.1*
Update	all	Minor changes
Change Ref.	*Section(s)*	*Issue 1.2*
TBD's frozen	all	TS temperatures
Opening T changed	Page 29	Opening at -25C
Setpoint HX	Page 56	Setpoint +80 C
TS frozen		

Summary

This document contains the safety analysis approach of the Tracker Thermal Control System. The AMS-02 TTCS system is to provide temperature control of the Tracker front-end electronics. The TTCS is comprised of a mechanically pumped two-phase CO_2 loop where heat is collected at evaporators inside the Tracker and rejected at two radiators. For reliability reasons, two redundant loops are implemented.

The objective of the safety analysis approach definition is to show that MDP is not exceeded in all cases. The maximum design pressure is based on the case where the entire TTSC loop has a maximum temperature of 65 °C.

The basic idea of the current safety approach makes use of the fact that several thermostat protected sections of the TTCS will stay well below the maximum design "pressure" temperature of the loop (65 °C). This gives us the ability to allow overheating above 65 °C in non thermostat protected section before reaching the maximum design pressure. By dividing the TTCS loop in;

- heated sections (with thermostat protection)
- heated sections (without thermostat protection)
- Unheated sections

and modelling the maximum temperatures of each section it is possible to show the overall TTCS MDP is not exceeded.

Contents

(76 pages in total)

1 Scope of the document

The document describes the TTCS maximum design pressure safety analysis approach.
It shows the TTCS system will stay below the MDP in operational and non-operational cases.

First the mean density of the TTCS loop is calculated based on the minimum and maximum accumulator liquid level, and the MDP of 160 bar.

In order to do the safety analysis, the loop is the divided in parts with different maximum temperatures. Subsequently the maximum temperatures for the defined parts are verified. This verification analyses are grouped in analyses for thermostat protected heated parts and non-protected heated parts.
Based on these results the maximum allowable temperature of unheated parts can be calculated as function of the maximum allowed accumulator temperature (i.e. the thermal switch protection temperature).

1.1 Purpose

The main purpose of the safety approach is to check if the MDP requirement is met in all situations.

2 Reference documents

	Title	
RD-1	TTCS heater specifications	AMSTR-NLR-043-Issue1.3
RD-2	TTCS Accumulator Thermal Safety Analysis	TTCS-SYSU-AN-001-2.0
RD-3	TTCS Condenser Freezing Test Report	AMSTR-NLR-039-Issue03

3 System overview

In Figure 3-3 and Figure 3-4 the primary and secondary piping lay-outs are shown. These lay-outs can be used as a reference to understand the operation and interactions of the components discussed.

An complete TTCS schematic including components and thermostats is shown in Figure 3-3 and Figure 3-4.

3.1 Loop subdivision

In order to perform the analyses the TTCS loop is divided in the following parts:

- Heated sections (with thermostat protected)
- Heated sections (without thermostat protection)
- Unheated section.

The tube dimensions and corresponding volume of the parts given in Table 3-1. In the same table it is indicated how much power is dissipated in the specified loop sections.

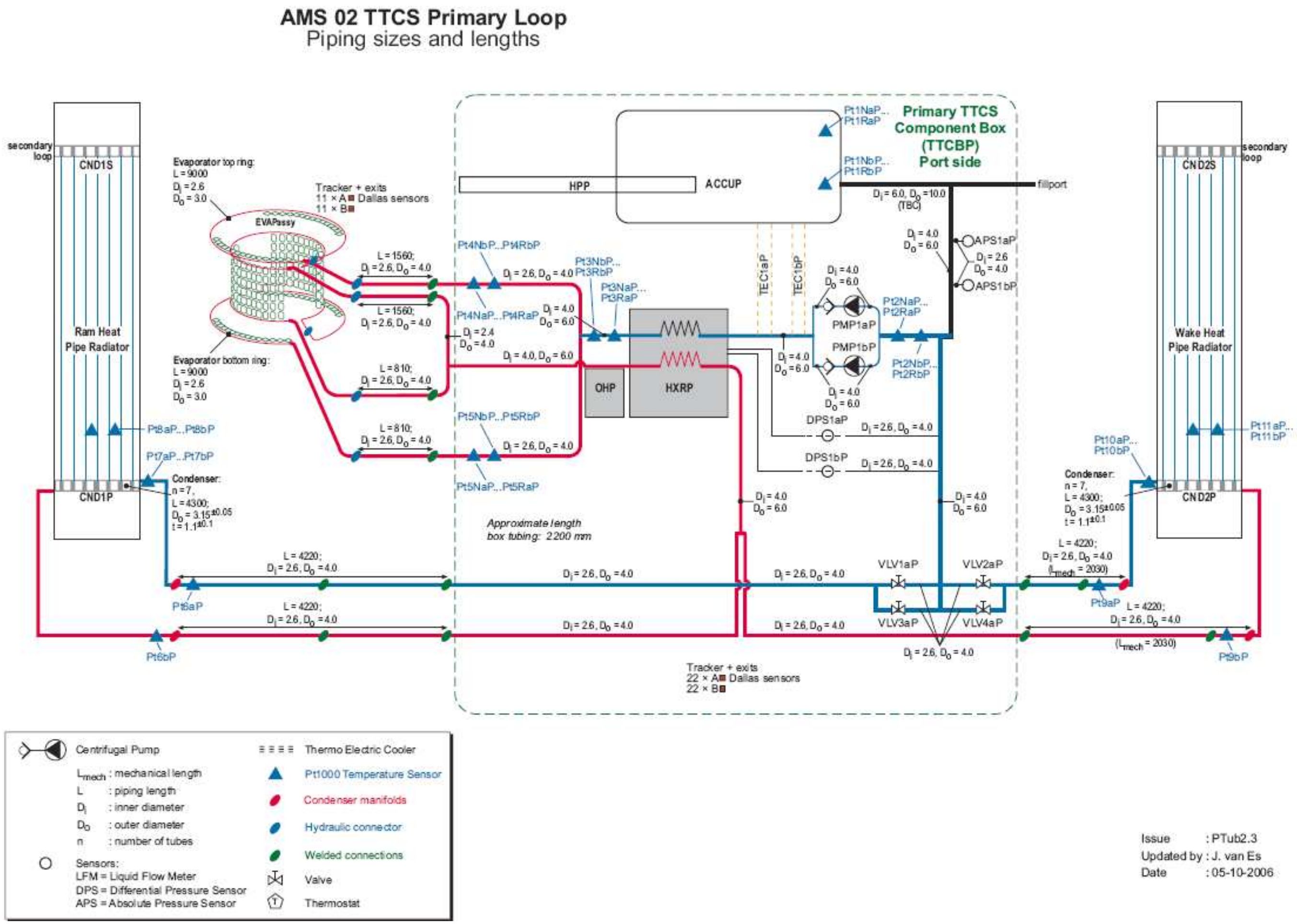

Figure 3-1: TTCS Primary loop lay-out (Piping sizing and length)

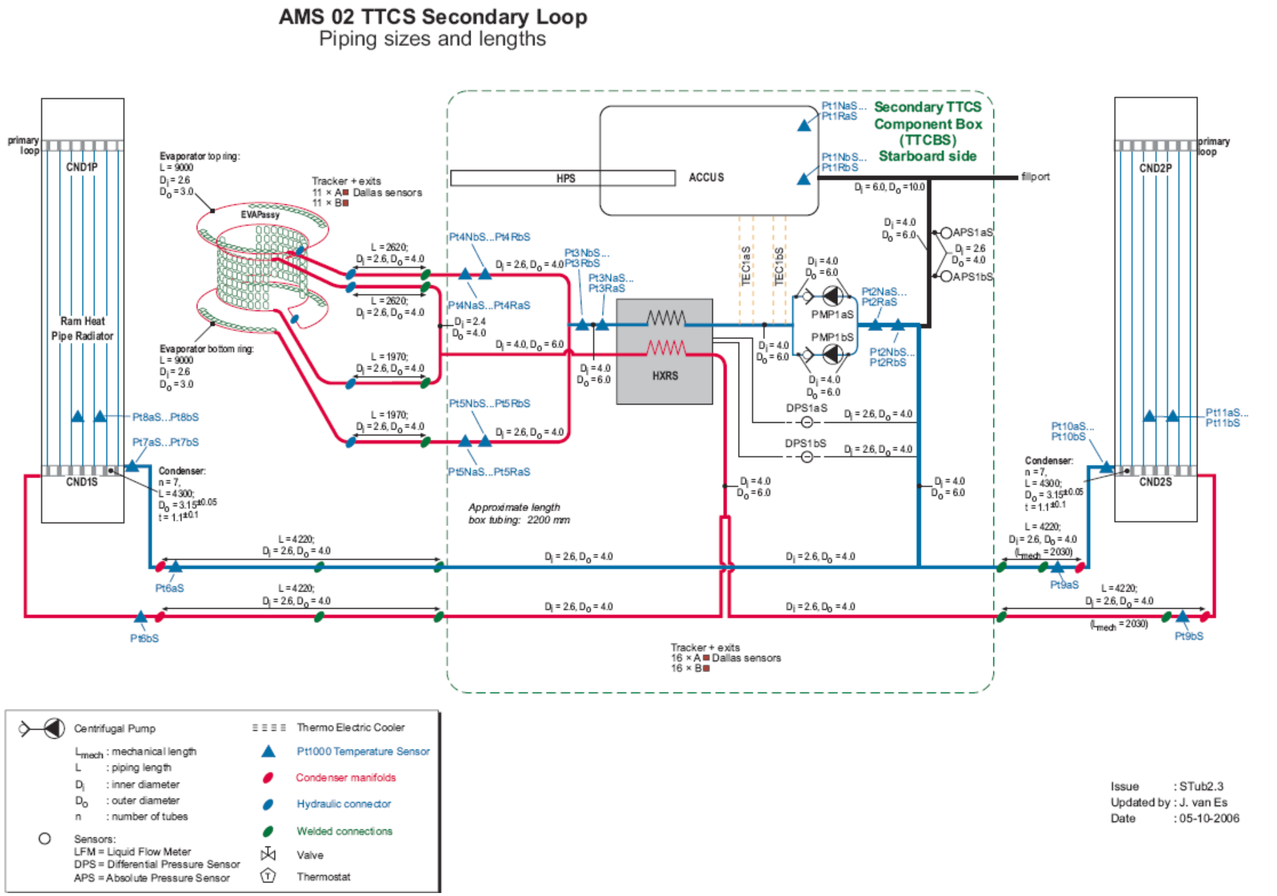

Figure 3-2: TTCS Secondary loop lay-out (Piping sizing and length)

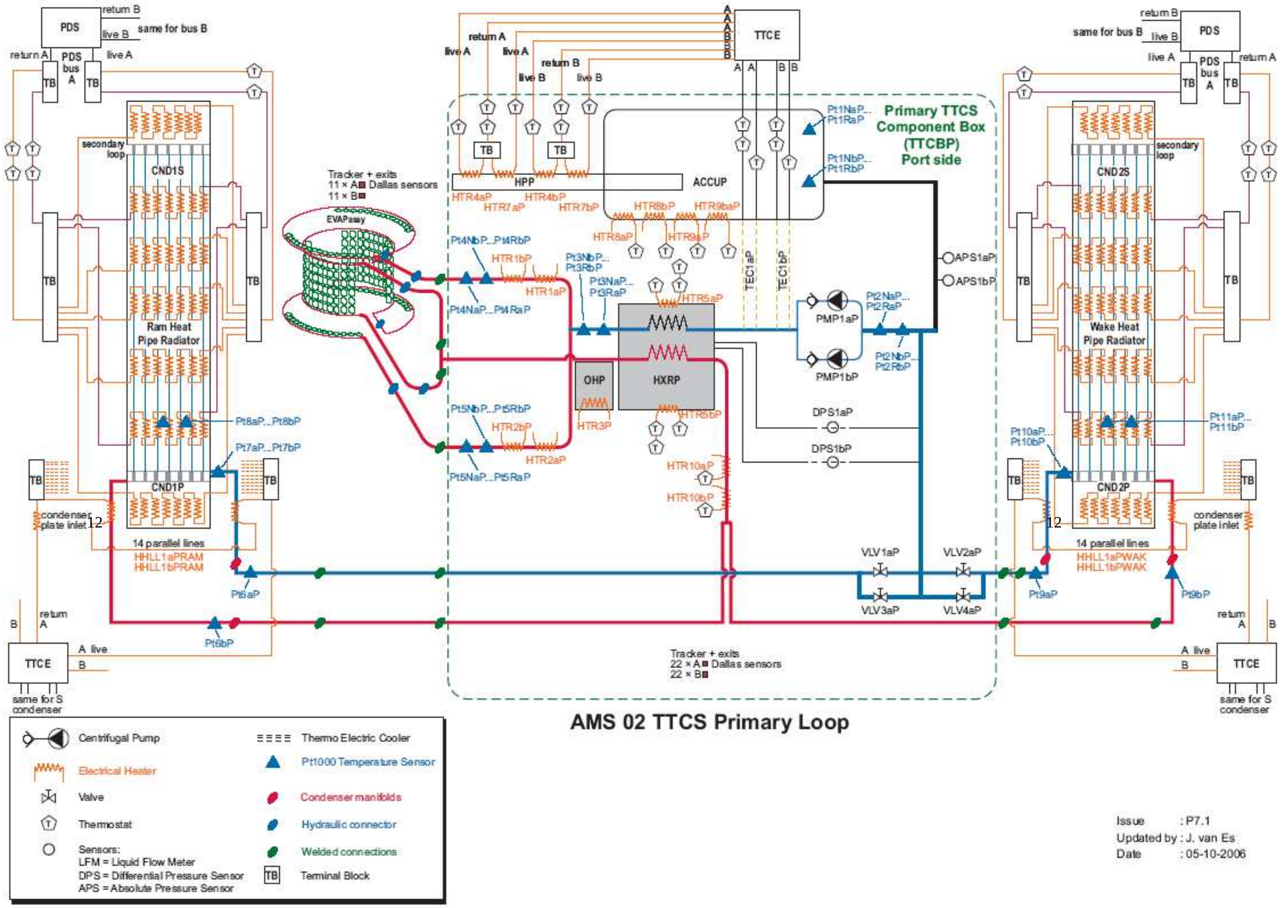

Figure 3-3: TTCS Primary loop lay-out (electronics schematic)

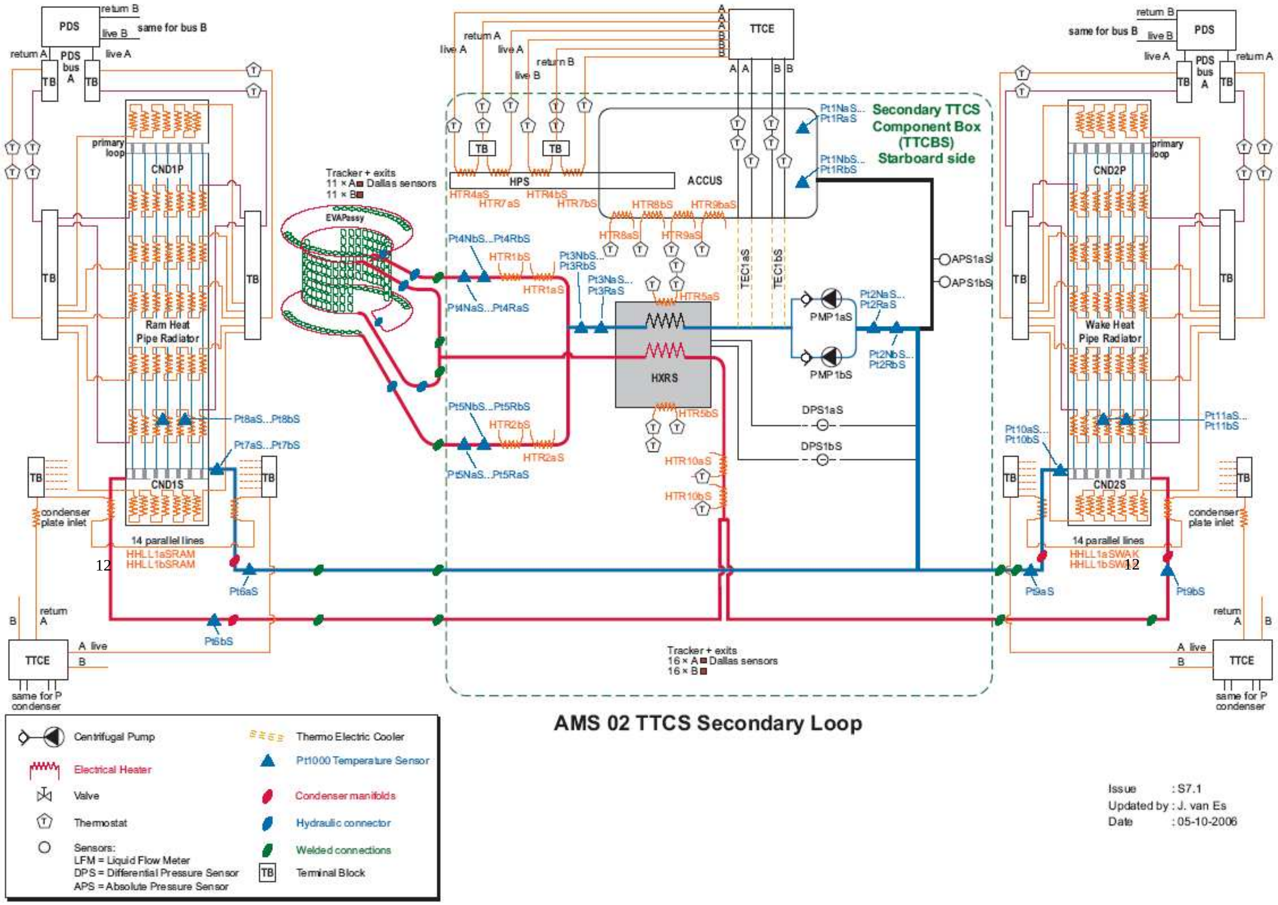

Figure 3-4: TTCS Secondary loop lay-out (electronics schematic)

3.2 TTCS Components overview and dimensions

In Table 3-1 an overview of the heaters and purpose of the heaters is given:

TTCS Primary Loop							
Component name	#	Tubing Dim		Total Internal Volume [ml]	Thermostat protection		Heater Power [Watt]
		D_{in} [mm]	L [m]		Y/N	Set-point [°C]	
Heated Components With Thermostats							
RAM capillary condenser lines	7	1.10	2.57	17.10	Y	-17.8	156
WAKE capillary condenser Lines	7	1.10	2.57	17.10	Y	-17.8	156
Accumulator	1	-	-	842	Y	55	75 (A+B)
Heat Exchanger	1	-	-	50	Y	80	100 (A+B)
Heated Components without Thermostats							
RAM capillary feed lines	7	1.10	0.7	4.65	N	-	11.2
WAKE capillary feed lines	7	1.10	0.7	4.65	N	-	11.2
TOP Evaporator	1	2.60	9.0	47.78	N	-	150
Lower Evaporator	1	2.60	9.0	47.78	N	-	150
NLR Experiment	1	4.00	0.3	3.77	N	-	49
Pump	2	-	-	60.00	N	-	4.0*
Valves	4	-	-	8.00	N	-	

Pre-Heater section	2	2.6	0.12		N		8.0
Cold Orbit Heater section	1	4.0	0.30		N		50
Unheated Parts without Thermostats							
RAM feed line	1	2.60	4.22	22.41	N	-	-
RAM Return line	1	2.60	4.22	22.41	N	-	-
WAKE feed line	1	2.60	4.22	22.41	N	-	-
WAKE Return line	1	2.60	4.22	22.41	N	-	-
Top Evaporator feed	1	2.60	1.56	08.28	N	-	-
Top Evaporator return	1	2.60	1.56	08.28	N	-	-
Lower Evaporator feed	1	2.60	0.81	04.30	N	-	-
Lower Evaporator return	1	2.60	0.81	04.30	N	-	-
Common evaporator out	1	4.00	0.20	02.51	N	-	-
Pump line in/out	1	4.00	0.50	06.28	N	-	-
Pressure sensor tubes	6	2.60	0.06	01.91	N	-	-
Pressure sensors +Flow Sensor	8	-	-	03.60	N	-	-
Hydraulic Connectors	6	-	-	00.45	N	-	-
Box tubing	1	2.60	2.20	11.68	N	-	-

Table 3-1: TTCS Components overview and dimensions

* worst case estimate based on 4 Watt at minimum flow (in reality the power will be less)

4 Introduction Safety approach

The maximum design conditions are based on the notion that the entire system pressure should not exceed 160 bar internal pressure and a maximum temperature (for the entire system) of 65 °C. The maximum allowable fill rate (system density) is directly determined from the Mollier diagram, seen in Figure 4-1, as the intersection between the blue line (constant temperature (65 °C) line) and the horizontal line of constant pressure.

In Figure 4-1 the Mollier diagram is seen for CO_2. The intersection of the T= 65 °C curve (blue line) with the ρ = 592.39 [kg/m^3] (red line) occurs at a pressure of 160 Bars:

- Max Design Pressure 160 [Bar]
- Max Design Temperature 65 [°C]
- Max Design Density 592.39 [kg/m^3] (=mass/volume)

The above pressure, density and temperature relations are based on the notion of constant temperature over the entire system. If the temperature of a part of the loop is below the 65 degrees the required volume to contain the CO_2 @ 160 Bars is smaller than the actual loop volume. This implies that the other parts of the loop can get warmer without exceeding the 160 Bars in pressure.

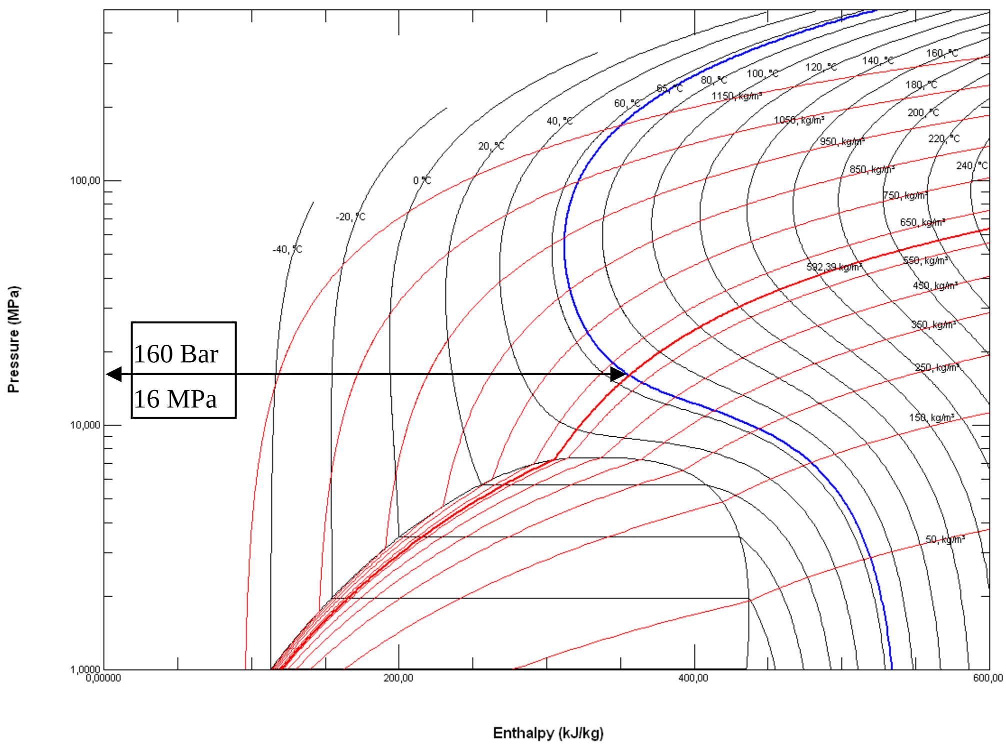

Figure 4-1: Mollier diagram

The safety approach makes use of this property. A flow diagram of the approach is shown in Figure 4-2. The sequential steps can be summarised as follows:

1. Determine the accumulator volume, and the system filling rate and/or density.
2. The loop is subdivided in the following parts:
    a. Heated sections (with thermostat protected)
    b. Heated sections (without thermostat protection)
    c. Unheated section.
3. Determine the maximum temperatures in the heated and unprotected components of the loop.
4. Determine the maximum allowable accumulator temperature as a function of the unheated components temperature such that P_{TTCS} < MDP (160 bar).
5. Check/show by modelling that the temperatures stay below the limits. (limits are the temperatures of the components such that the overall system pressure is equal to the 160 bar)
6. If the temperature of the unheated parts stays below the chosen value (corresponding with an accumulator temperature) @ worse conditions (hot) then the design is safe.

In the remainder of the document the approach as presented in Figure 4-2 is followed and point by point. In section 5 first an the minimum accumulator volume is calculated. Subsequently in section 6 an overview of the thermostats and heaters is given elucidating the division in sections. In section 7 the maximum occurring temperature per section are determined by tests. With these temperatures the final safety is demonstrated in section 8. Based on the results a final switch temperature of the accumulator can be chosen.

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Figure 4-2: TTCS Safety analysis flow diagram

5 Accumulator minimum volume determination

First of all the minimum accumulator volume is calculated as indicated in yellow in the approach flow diagram.

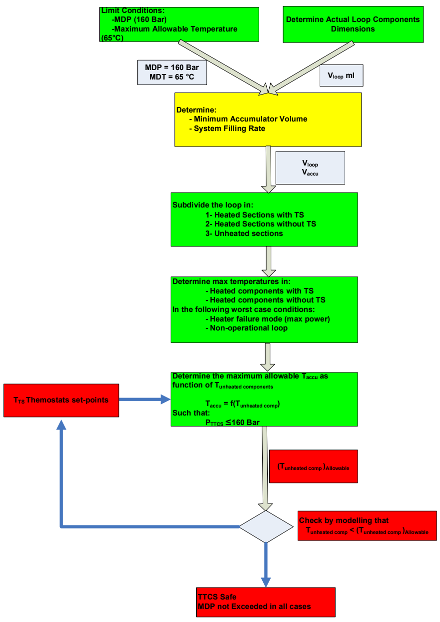


Figure 5-1: Step 1 in the approach

In this section the minimum allowed accumulator volume is calculated. The approach is elucidated and the calculation steps and results are presented. The final calculated minimum allowed volume is smaller then the final accumulator volume. This gives a small additional margin on the safety approach. However as the final accumulator is not yet known the minimum value is used in the final safety calculation in section 8.

5.1 Accumulator volume requirements

The functions of the accumulator volume in the loop are:

1. Under conditions where the loop contains liquid only (e.g. at start-up or AMS non-operation), the accumulator volume must be adequate to supply CO_2 to the loop or take-in CO_2 from the loop, because of liquid volume variations due to possible loop temperature variations over the working rang (-20^0 C <-> + 20^0 C).
2. Under conditions where loop elements (evaporator, condensers' feed lines, condensers) are (partly) filled with 2-phase CO_2, the accumulator volume must be suited to take in the surplus CO_2 from the loop.

Under all circumstances the accumulator must contain a certain amount (10%) of CO_2-liquid (liquid content in accumulator will be lowest when loop is completely filled with CO_2-liquid), such that it is prevented at all times that vapour from the accumulator enters the pump suction line.

Furthermore it is desirable that:

a) Accumulator volume is minimized (because of mass and volume budgets)

5.2 Calculation Approach

The accumulator volume is determined following the iterative process described below:

A. Determine the loop volume from the design of the current design of the TTCS, (Including components volumes).
B. Determine the case were the maximum amount of working fluid is in the loop.
    a. The loop at cold temperatures
    b. The accumulator at hot temperature.
C. Assume an accumulator volume.
D. Determine the maximum design pressure and thus the maximum allowable Fill Charge.
E. Determine the fill charge accuracy and thus the minimum TTCS fill charge.
F. Determine the total End Of Life (EOL) Fill Charge (FC) ==> $(FC_{tot})_{EOL}$
G. Determine the working liquid mass in the loop.
H. Determine the FC in the accumulator such that the volume of the liquid in the accumulator is 10 % of the total accumulator volume.
I. Determine the accumulator fill charge.
J. Determine the accumulator volume.

Change the input accumulator volume in step C and rerun the calculations until the output accumulator volume equals the input accumulator volume.

Filling ratio definition

The filling ratio is defined as:

$$FR = \frac{m_{tot}}{V_{accu} + V_{loop}} = \frac{m_{accu} + m_{loop}}{V_{accu} + V_{loop}} \qquad \textbf{(1)}$$

Where:

m_{accu}= Total CO_2-mass in accu

m_{loop}= Total CO_2-mass in loop

V_{accu}= Total CO_2-volume in accu

V_{loop}= Total CO_2-volume in loop

As starting condition we assume a minimum filling, such that the loop is completely filled with CO_2-liquid and the accu completely filled with CO_2-vapour only:

$$m_{accu}=\rho_v*V_{accu} \qquad (3)$$

$$m_{loop}=\rho_l*V_{loop} \qquad (4)$$

Finally (in step H) also the 10% minimum liquid volume is taken into account. The iterative process finally ends in step J with the final minimum allowed accumulator volume.

5.3 Accumulator minimum volume calculations

In this section the accumulator volume is calculated following the step by step approach.

Step A:

The loop volume of the current (September 2006) design is seen in Table 3-1 in section 3.2.

Step B:

The following assumptions are made concerning the temperature distribution in the TTCS loop; these conditions determine the case where the accumulator contains the minimum amount of liquid:

Group	Description	Temp [°C]	Components	Density [g/l]
1	Cold parts of the loop	-55	Radiator feed lines Radiator return lines Condenser capillary lines	1172.9 (liquid)
2	Hot parts of the loop	-20	Entire loop except group 1	1031.7 (vapour)
3	Accumulator	+20	Accumulator	773.3 (liquid) 194.2 (vapour)

Step C:

The volume of the accumulator is assumed to be:

$$V_{accu} = 0.842 \text{ [l]}$$

This value resulted from the iterative process described above where the calculated accumulator volume from step J is equal to the assumed accumulator volume from step C.

Step D:

Determine of the maximum allowable design pressure and the maximum allowable fill charge.

		Comment
Design Pressure	160 [Bar]	-
Max Temperature	65 [°C]	For the entire loop
Resulting density for CO_2	592.39 [g/l]	From NIST Data

As stated before the fill charge (FC) of the TTCS loop is defined as total CO_2 mass divided by the total loop volume $V_{TTCS} = V_{accu} + V_{loop}$.

The maximum design pressure and temperature gives us the maximum allowable fill charge:

$$\mathbf{FC_{tot\_BOL\_max} = 592.39\ [g/l]}$$

Step E:

Determination the fill charge accuracy, dFC. The total fill charge accuracy is obtained by making assumptions concerning the accuracy of the total volume and the total CO_2 mass in the loop.

$$FC = \frac{TotalMass}{TotalVolume}$$

The relative error in fill charge is equal to the sum of the errors in the mass determination and the volume determination of the entire loop.

$$\frac{dFC}{FC} = \frac{dm}{m} + \frac{dV}{V}$$

For the accuracy of the mass and volume determination the following two values are assumed:

$$\frac{dm}{m} = \pm 2\%$$

$$\frac{dV}{V} = \pm 2\%$$

These results in following maximum fill charge error during the filling process:

$$\frac{dFC}{FC} = \pm 2\% + \pm 2\% = \pm 4\%$$

The total maximum allowable fill charge:

$$(FC)_{\max} = 592.39[g/l]$$

This maximum allowable fill charge should be never exceeded, since it is directly related to the maximum design pressure. This implies that the set point for the filling process should be $(FC_{tot\_BOL})_{SetPoint}$.

$$(FC_{tot\_BOL})_{SetPoint} = \frac{(FC)_{max}}{(1 + dFC/FC)}[g/l]$$
$$(FC_{tot\_BOL})_{SetPoint} = 569.60[g/l]$$

This BOL fill charge set points results in a minimum BOL fill charge due to errors during the filling process (mass and volume):

$$(FC_{tot\_BOL})_{min} = (FC_{tot\_BOL})_{SetPoint} * (1 - \frac{dFC}{FC})[g/l]$$
$$(FC_{tot\_BOL})_{min} = 546.82[g/l]$$

The above describe values are summarized in the following table:

		Comment
Accuracy mass determination	$\frac{dm}{m} = \pm 2\%$	
Accuracy Volume Determination	$\frac{dV}{V} = \pm 2\%$	
Max Fill Charge Error	$\frac{dFC}{FC} = \pm 4\%$	
Max Allowable Fill Charge	$(FC)_{max} = 592.39[g/l]$	
Fill Charge Set-point	$(FC_{tot\_BOL})_{SetPoint} = 569.60[g/l]$	
Minimum Begin of Life Fill Charge	$(FC_{tot\_BOL})_{min} = 546.82[g/l]$	

Step L:

Determine the total End Of Life (EOL) Fill Charge (FC) ==> $(FC_{tot})_{EOL.}$ The assumption is made that the TTCS has such a total leak rate that at the end of life the TTCS lost 30 g of its total CO_2 mass.

$$SL_{tot} = TotalSystemLeak$$
$$SL_{tot} = 30[g]$$

This is the minimum Fill Charge of TTCS system:

$$(FC_{tot})_{EOL} = (FC_{tot\_BOL})_{min} - \frac{SL_{tot}}{V_{tot}}$$
$$(FC_{tot})_{EOL} = 522.74[g/l]$$

5.4 Summary en conclusions

In this chapter the TTCS loop fill density has been defined based on:

- Minimum accumulator liquid level
- Maximum accumulator liquid level
- MDP of 160 Bar
- Loop Volume (without accumulator) = 0.413 [l]

This resulted in the minimum accumulator volume and mean loop fill density/rate:

- V_{accu} = 0.842 [l]
- $(FC)_{\max} = 592.39[g/l]$

These values are used in the final safety calculation in section 8.

6 TTSC Thermostats overview

In this chapter the overview of the thermostats in the TTCS is provided. This is important to understand the division in sections of the loop and is part of step 2 in the approach.

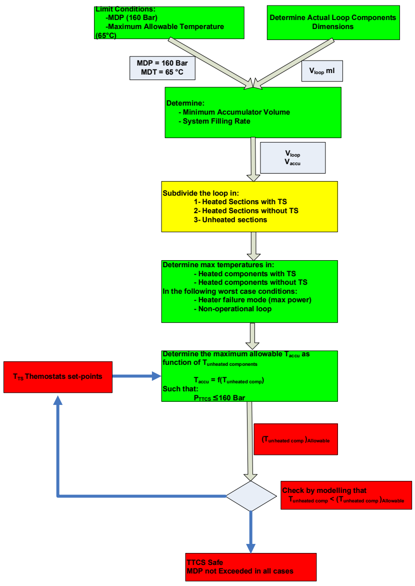


Figure 6-1: Step 2 in the approach

The TTCS loop is divided in three types of sections.

- Heated sections with thermostat protection
- Heated sections without thermostat protection
- Unheated sections

The thermostat protected sections are:

1. Accumulator Flight Operation heaters
2. Accumulator Flight Emergency heaters
3. Accumulator Ground Operation heaters
4. Accumulator Ground Emergency heaters
5. Start-up heaters
6. Tracker Radiator/Condenser

The thermostats non-protected but heated sections are:

1. Cold orbit heaters
2. Pre-heaters
3. OHP heaters

The heaters are described in detail (numbers of heaters, locations and electronics schematics) in the heaters specifications document “AMSTR-NLR-TN-043”, an overview is shown in Table 6-1.

Table 6-1: TTCS Heater overview

Heater name	**Control**		**Purpose**	**Power/ Heater @28Vol**
	T-stat	**S/W control**		
TTCS 28 Volt heaters				
Pre-heaters		X	Raise sub-cooled liquid to TTCS set-point	8.9
Accumulator operational heater	XX	X	Keep accumulator (TTCS) at set-point	22.5
Accumulator Emergency heater	XX	X	Quick raise of accumulator set-point	15.0
Accumulator control heaters (ground testing)	XX	X	Keep accumulator (TTCS) at set-point	22.5
Accumulator Emergency heaters(ground testing)	XX	X	Quick raise of accumulator set-point	15.0
Start-up heaters	XX	X	Raise TTCS liquid flow from – 40 °C to – 20°C during start-up	55.8
OHP heater		X	Operate OHP experiment in cold orbit operation only	50.0
TTCS liquid line heaters		X	Defrost the TTCS condenser lines	16.91
Cold Orbit Heaters	XXX	X	Prevent Freezing in the Condenser @ Cold Orbits	60
Tracker rad; condenser heaters RAM	X		Defrost Tracker radiator NH_3 HP’s and CO_2 condenser	75.75
Tracker rad; condenser heaters WAKE	X		Defrost Tracker radiator NH_3 HP’s and CO_2 condenser	175.75

X = Nominal control
XX = Additional safety control (outside operational TTCS temperature limits)
XXX = Additional mission success control (outside operational TTCS temperature limits)

The TTCS heaters are divided in 120 VDC heaters and 28 VDC heaters.

The radiator heaters run at 120 VDC from the PDS. Two redundant heaters branches are present. The A heaters are supplied by the PDS A, and the redundant heaters are supplied by the redundant PDS B.

All other TTCS heaters run from the 28VDC supplied by the PDS to the TT-Crate (TTCE). The TTCE has a nominal and redundant feed (TTCE A and TTCE B). The TTCE A (main TTCE) can be supplied by both A and B of the PDS. The same is applicable for the TTCE B (redundant TTCE).
The power supplied from the TTCE is @ a nominal voltage of 28.0 Volts (min: 26.5 Volts max: 29.5 Volts). All the heaters are sized with the nominal voltage (28.0 Volts) except for the heaters with have to output a minimum power output even @ minimum voltage, these are sized with the minimum voltage (26.5 Volts).

6.1 TTCS 28.0 Volts heaters

The thermostat protected TTCS 28 V heaters are the accumulator heaters and TEC-coolers on the accumulator and the start-up heaters on the heat exchanger. The thermostat rationale of both locations is explained below.

6.1.1 Accumulator thermostats

For the Accumulator flight heaters 3 heat switches are foreseen for the both emergency and control heaters. In order to reduce the number of heat switches on the accumulator heat pipe, the return lines of the emergency and control heaters are combined. The two heat switches protect both heaters at once. On each life line one thermostat is placed while two thermostats are placed on the two combined return lines as seen in Figure 6-2.
The ground test heaters will be protected by a single heat switch for safety reasons during ground testing. These ground test heaters will be disconnected after ground testing and therefore during flight. The procedure for disconnecting the ground test heaters is yet to be written.
The accumulator heaters layout with thermostats is seen in Figure 6-2. The heaters numbering is presented in Table 6-2.

Heater Function	Primary Box			Secondary Box		
	Heater Id#	Power@ 28 Vdc	TS Switch Temp °C	Heater Id#	TS Switch Temp °C	Power @ 28 Vdc
Flight Control	HTR4aP	22.5	+55	HTR4aS	+55	22.5
Ground Test Control	HTR8aP	22.2	+55	HTR8aS	+55	22.2
Flight Emergency	HTR7aP	15	+55	HTR7aS	+55	15
Ground Test Emergency	HTR9aP	14.9	+55	HTR9aS	+55	14.9
Flight Control	HTR4bP	22.5	+55	HTR4bS	+55	22.5
Ground Test Control	HTR8bP	22.2	+55	HTR8bS	+55	22.2
Flight Emergency	HTR7bP	15	+55	HTR7bS	+55	15
Ground Test Emergency	HTR9bP	14.9	+55	HTR9bS	+55	14.9

Table 6-2: Accumulator heater table (yellow flight heaters, green ground testing heaters) 5and thermal switches

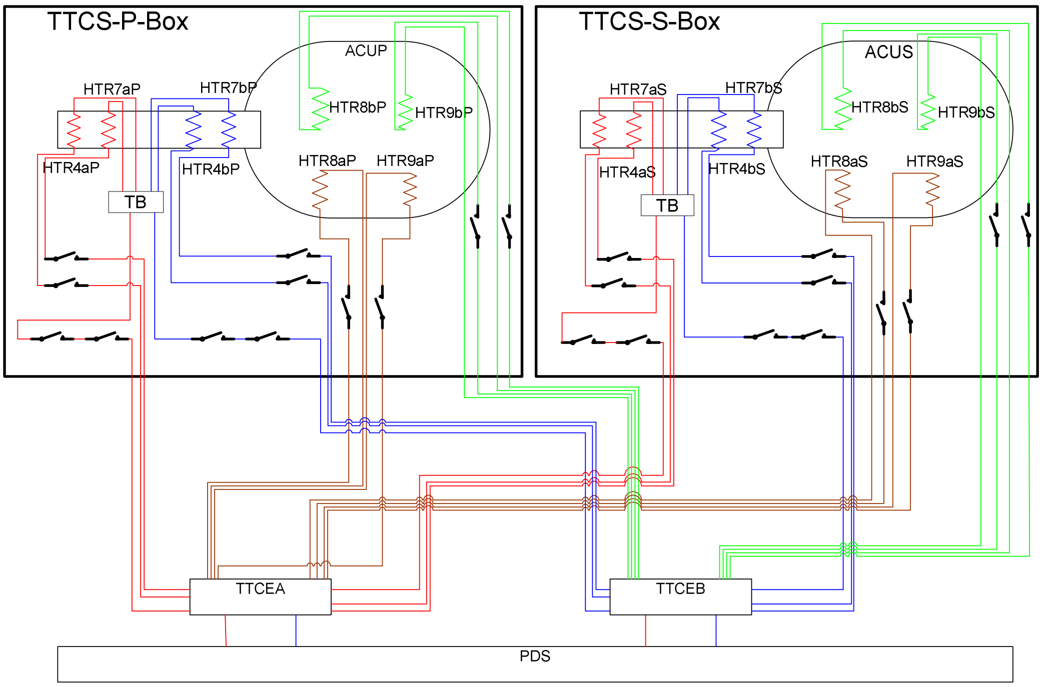


Figure 6-2: Accumulator heater schematic with thermostats

The thermostats selected for the accumulator are:

- Series 3200 High Reliability Aerospace Thermostats (Honeywell/Elmwood) with the following characteristics (Type: T116):
    - Max weight is 8 gram each
    - Life cycles:
        - 100,000 cycles at 4 [A] / 30 [Vdc]
        - 20,000 cycles at 4.5 [A] / 32 [Vdc]
        - 20,000 cycles at 1.2 [A] / 126 [Vdc]
    - Temperature set point is from -50 [°C] to +150 [°C]
    - Tolerances on nominal close/open set point is +/- 1.7 [°C]
    - Minimum differential temperature between nominal open/close set point (thermostat hysteresis band) regardless switching tolerances is 4.4 [°C].

The layout of the thermostat is seen in Figure 6-3.

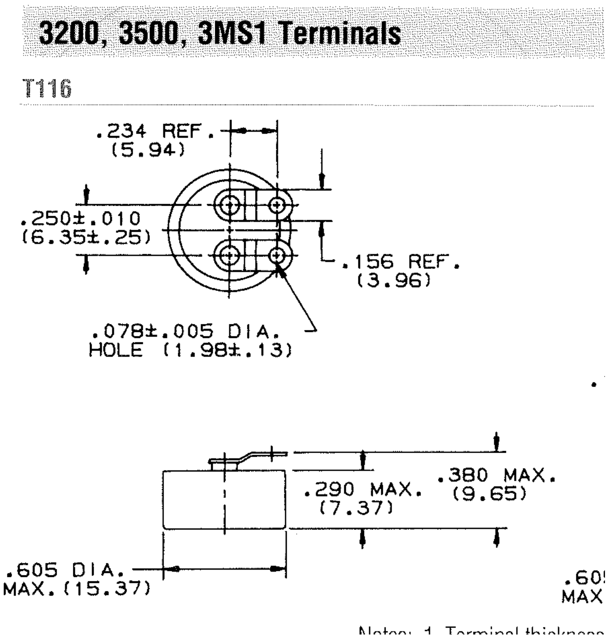


Figure 6-3: TTCS-BOX Thermostats Design

6.1.2 Start-up heaters thermostats

The start-up heaters are protected by 3 thermal switches in series with the stat-up heater for safety reasons. The thermostats are located on the upper bracket as seen in Figure 6-4.

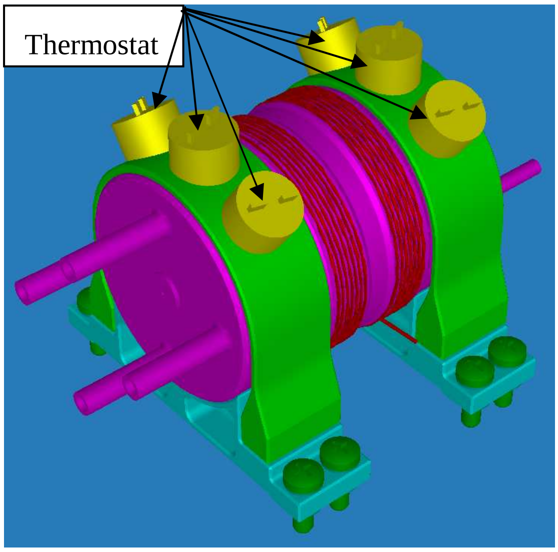


Figure 6-4: Thermostat and wire heaters placement onto the TTCS heat exchanger

The thermostats chosen are the same as for the accumulator heaters seen section 6.1.2, *"Series 3200 High Reliability Aerospace Thermostats (Honeywell/Elmwood) with the following characteristics (Type: T116)"*.

On each live power line one thermostat is placed while on each return lines two thermostats are placed.

Heater Function	Primary Box			Secondary Box		
	Heater Id#	**Power@ 28 Vdc**	**TS Switch Temp °C**	**Heater Id#**	**TS Switch Temp °C**	**Power @ 28 Vdc**
Start-up heater	HTR5aP	55.8	**+80**	HTR4aS	**+80**	55.8
Start-up heater	HTR6bP	55.8	**+80**	HTR8aS	**+80**	55.8

6.2 TTCS 120 Volt Heaters

Each tracker radiator panel is equipped with 120 Vdc Kapton foil heaters glued on the radiator backside face sheet in the area of the heat pipes.

The heaters are organized in 7 parallel branches along the 7 embedded heat pipes. Five are divided over the radiator and two branches are divided over the condenser (one for each condenser). Condensers (mounted on the backside of the radiator panel) are equipped with 120Vdc Kapton foil heaters as well. In each branch, the condenser heaters and radiator heaters are in series.

The 120V heaters are powered respectively bus A and B of the PDS.

Heater operation is controlled by means of PDS switch and mechanical thermostats. The location of the thermostat is on the condenser plate, exact location is to be defined.
All heaters on one Tracker radiator including condensers heaters are switched by thermostats at the same temperature on the same location. For integration reasons the thermostats will be located on the condenser construction. The electronic layout of the radiator heaters with thermostats is seen in Figure 6-5.
The thermostats rationale is as follows:

- For safety critical condenser heater branches located on the CO_2 condensers one (1) thermostat is located in the power feed line and two (2) in the return line.
- The same is done for the radiator heaters.

Thermostat set-point for all thermostats in the tracker radiator/condenser heaters:

- Nominal operation (NO heat)
- Threshold temperature for closing: -35 °C
- Threshold temperature for opening: -25 °C

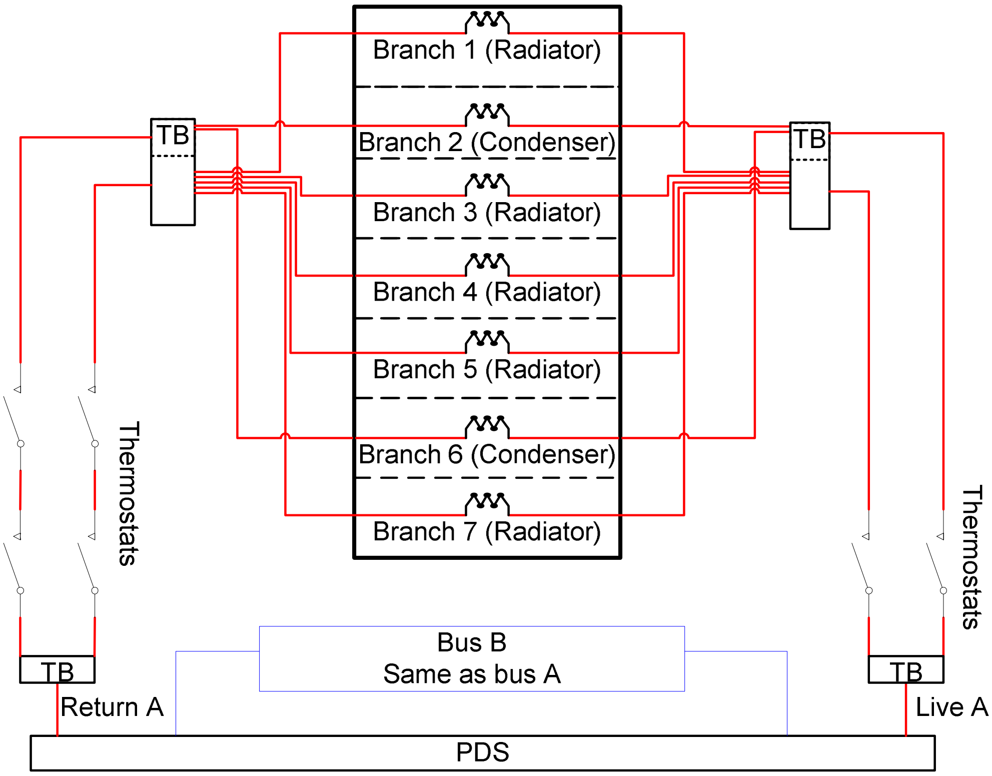


Figure 6-5: Tracker radiator/condenser heater electronic lay-out with thermostats.

The heater design with thermostats is two-fault tolerant for the condenser heaters and the design is therefore inherent safe. The condenser heaters can not raise the temperature of the condensers to the Maximum Design Temperature of -5 °C during melting (**see also NLR-Memorandum AMSTR-NLR-039-Issue03 "TTCS Condenser Freezing Test Report"**). The same thermostat configuration is applicable for the radiator branches.

The thermostats chose on the radiator are the **700 series Thermal Switch** from **Honeywell** having the following characteristics:

- Ambient Temperature Range: -201 °C to +204 °C
- Specified temp Set point range: -49 °C to -17.8 °C
- Standard set-point tolerance: ±3.3 °C
- The 700 series has supporting data at 1 amp 120 VDC

The thermostats are clued onto the condenser and the radiator structure. In Figure 6-6 the layout of the **Honeywell 700 series** thermostats is seen.

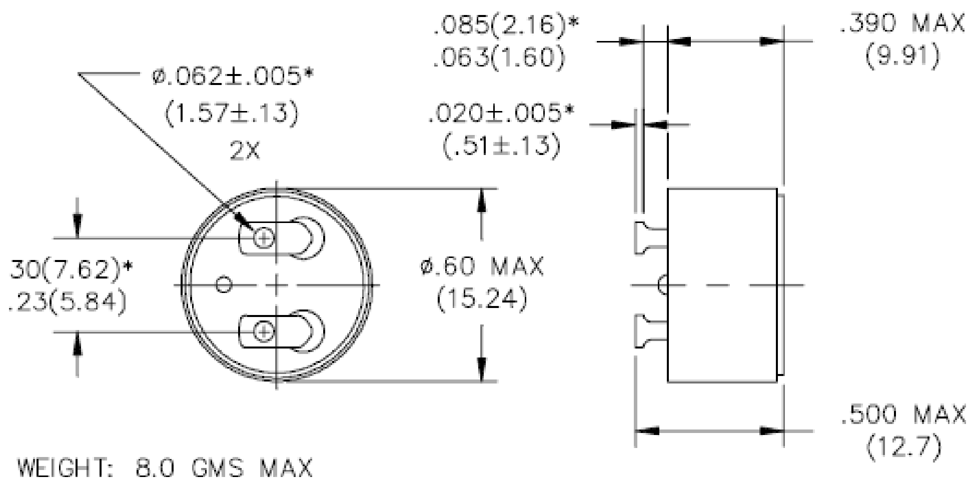


Figure 6-6: Honeywell 700 series layout (dimensions in inches)

The power distribution per branch @ 126.5 Volts is summarized in Table 6-3. The maximum current through the thermostats stays below the 1 Amp limit.

	Branch number	Branch Resistance [Ω]	Current [A] @126.5 V	TS Current [A] @ 126.5 V	Power [W] @ 126.5 V
Rad	1	729.5	0.173	**0.889**	21.94
	3	697.9	0.181		22.93
	4	697.9	0.181		22.93
	5	697.9	0.181		22.93
	7	729.5	0.173		21.94
Cond	2	387.2	0.327	**0.654**	41.33
	6	387.2	0.327		41.33
	Total	**81.93**	**1.543**		**195.33**

Table 6-3: Power current distribution @ 126.5 Vdc over the branches, (TS: thermostats)

7 Thermal/Fluid model heated TTCS Components

The purpose of the thermal/fluid modelling of the TTCS components is to quantify the maximum occurring temperatures in the case of heater control failure.

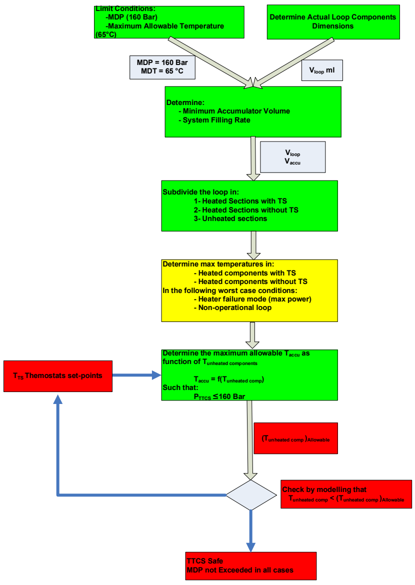


Figure 7-1: Step 3 in the approach

The following components of the TTCS are modelled and the results are presented in this chapter:

1. Pre-heater
2. Cold orbit heater
3. Start-up heater
4. Radiator capillary feed and return lines heaters
5. Oscillating heat pipe heaters

The maximum temperatures of the remaining heated components,

6. Accumulator heaters
7. Tracker condenser heaters
8. Evaporators

are analysed and documented separately.

7.1 Pre-Heater

7.1.1 Pre-Heater Design

The pre-heater properties are summarized as follows:

Function: The objective of the pre-heaters is to raise the CO_2 temperature to the set-point temperature.

Location: The pre-heaters are located in the TTCS-boxes after the split of the evaporator tubing. At both branches a redundant pre-heater is located. One of the evaporator branches is routed to the upper Tracker and the other to the lower Tracker. The pre-heater section will be located directly on the TTCS base-plate and the heaters will be connected directly to the TTCS tubes, seen in the Figure 7-2.

Heater design: The Pre-heater is a wire heater soldered onto the piping of the TTCS, with the following properties:

- R = 87.8 Ohm
- P_{min} = $26.5^2/87.8$ = 8.00 Watt
- P_{nom} = $28.0^2/87.8$ = 8.92 Watt
- P_{max} = $29.5^2/87.8$ = 9.91 Watt

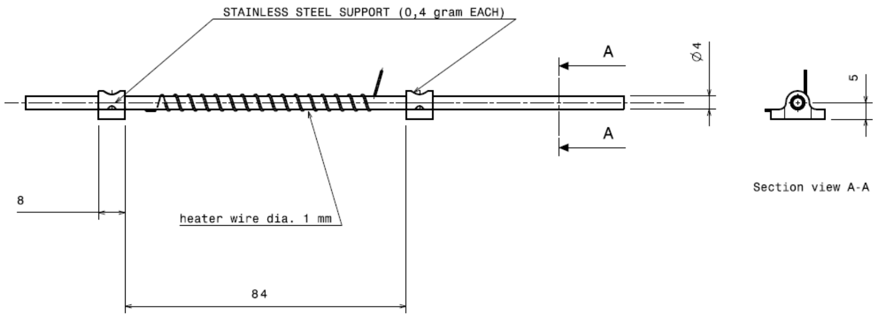


Figure 7-2: Pre-heater design

7.1.2 Pre-Heater Model

The purpose of the presented thermal model is to check whether the length of the heated pre-heater section is sufficient to heat the sub-cooled CO_2 liquid coming from the heat exchanger and to check the maximum temperature at heater control failure.

The pre-heater model is implanted in Sinda/Fluint. The thermal model divides the heated pre-heater tube in seven sections as seen in Figure 7-5.

In the present study the Pre-heater is part of a small liquid loop, seen in Figure 7-3. In this small loop it is easy to set the pre-heater ingoing temperature T_{in} and the saturation set point $T_{set\ point}$. The pre-heater is modelled as a heat exchanger seen in Figure 7-3 as HX-3.

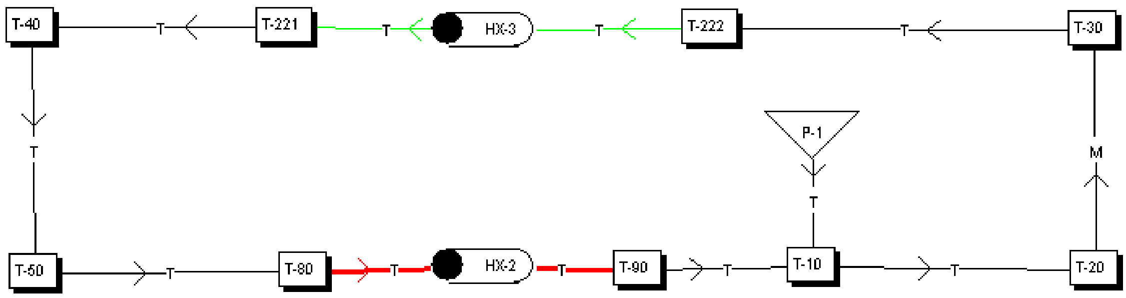


Figure 7-3: Small fluid loop with pre-heater (HX-3)

The fluid part of the heat exchanger (Pre-heater) is seen in Figure 7-4:

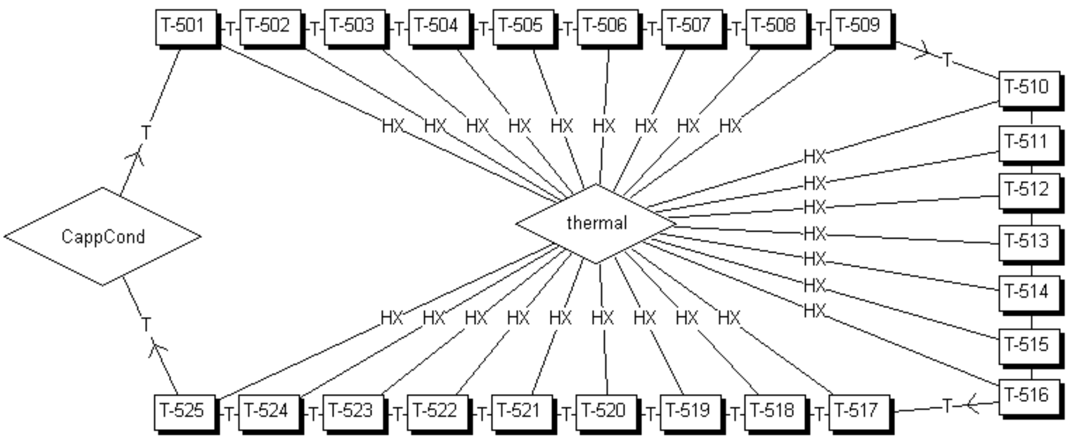


Figure 7-4: Pre-heater Fluid network

The thermal part of the Pre-heater model (tube nodes and the thermal connections) is seen in Figure 7-5.

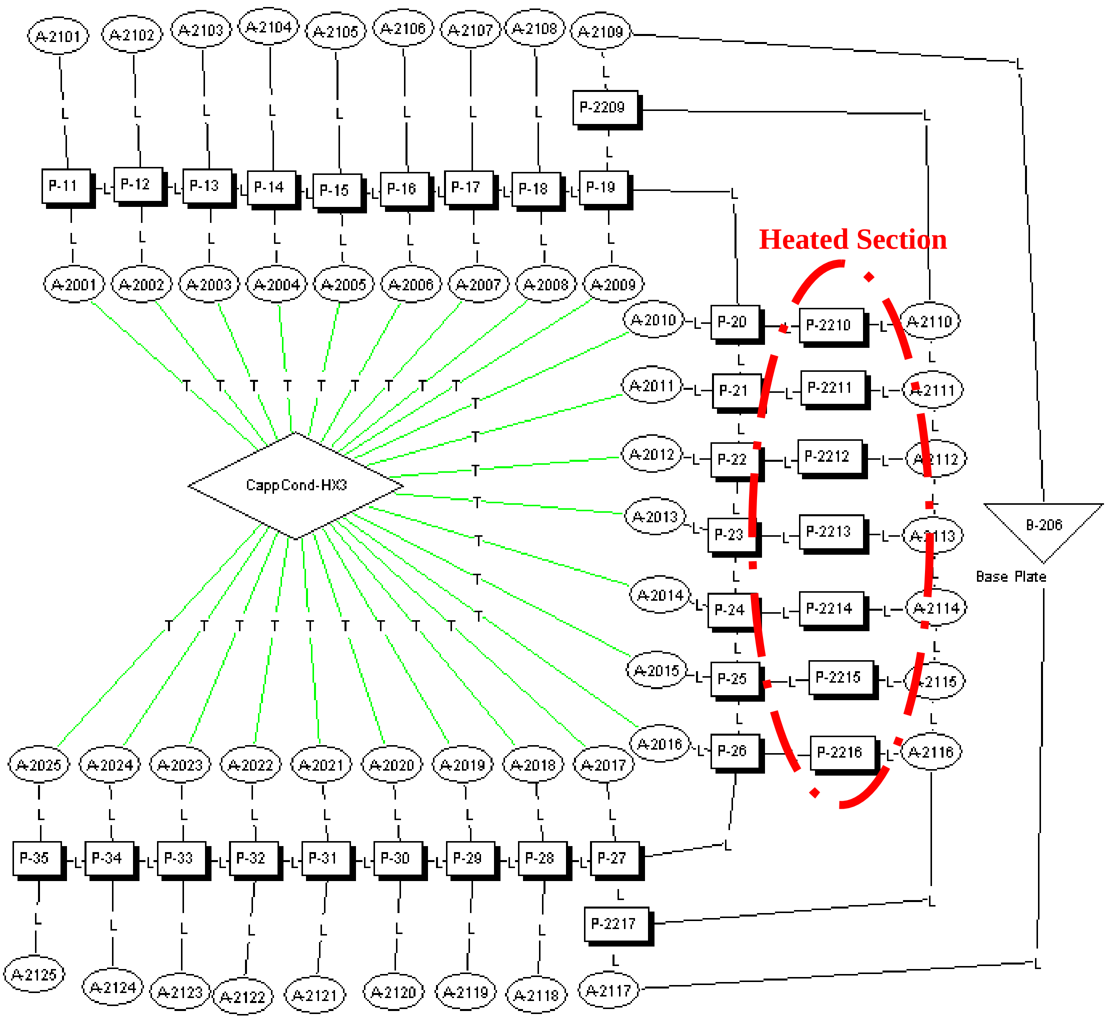


Figure 7-5: Pre-heater thermal network

The Pre-heater is connected with the base plate, which is modelled here as a thermal boundary node (B-206) having a constant temperature of 273 K. The connections between the copper blocks and the base plate are estimated having a thermal conductivity of 0.056 [W/K]. The estimation for the conductivity through the connection between the TTCS tube and the base plate is seen in Appendix A.

Operational case

In this section the operational case is discussed and the results are presented. The main objective is to quantify the ratio between the heat input in the fluid and the heat loss to the base plate.

The temperature in lumps before and after the pre-heater are shown Figure 7-6 for the nominal mass flow and minimal heater power:

- M = 2.0 g/s (Nominal)
- P_{heater} = 8.0 Watt

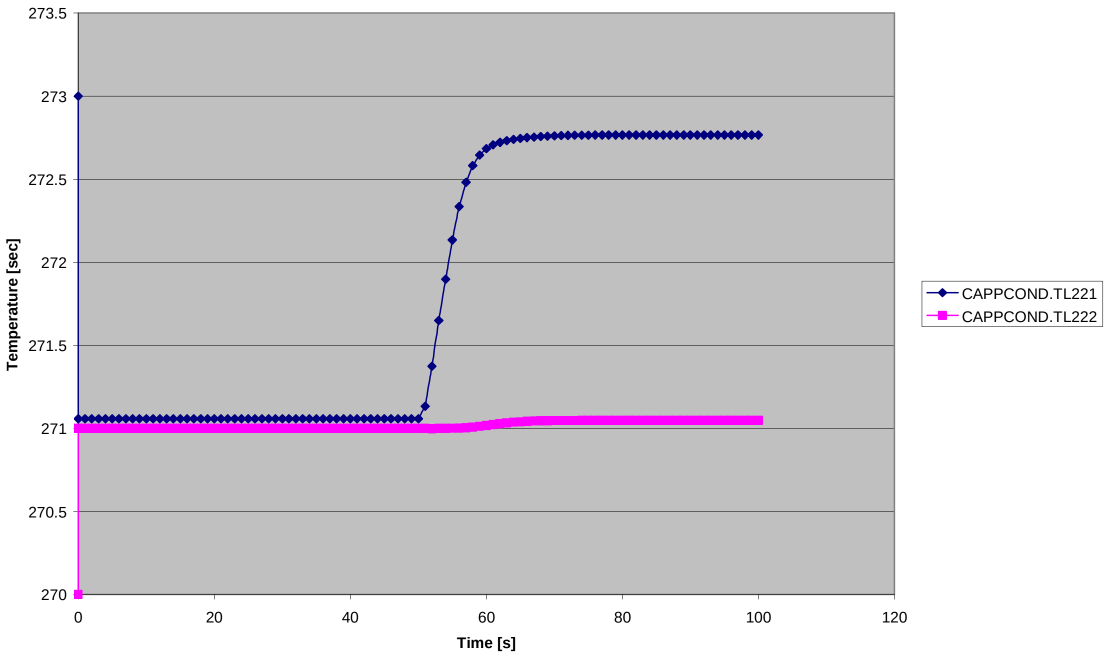


Figure 7-6: Temperature before (a) and after (b) the pre-heater during TTCS operation

The pre-heater is able to raise the liquid temperature with 1.72 K. The heat input in the liquid lumps is given in Figure 7-7. The model is made such that the heater is switched on @ time = 50 seconds.

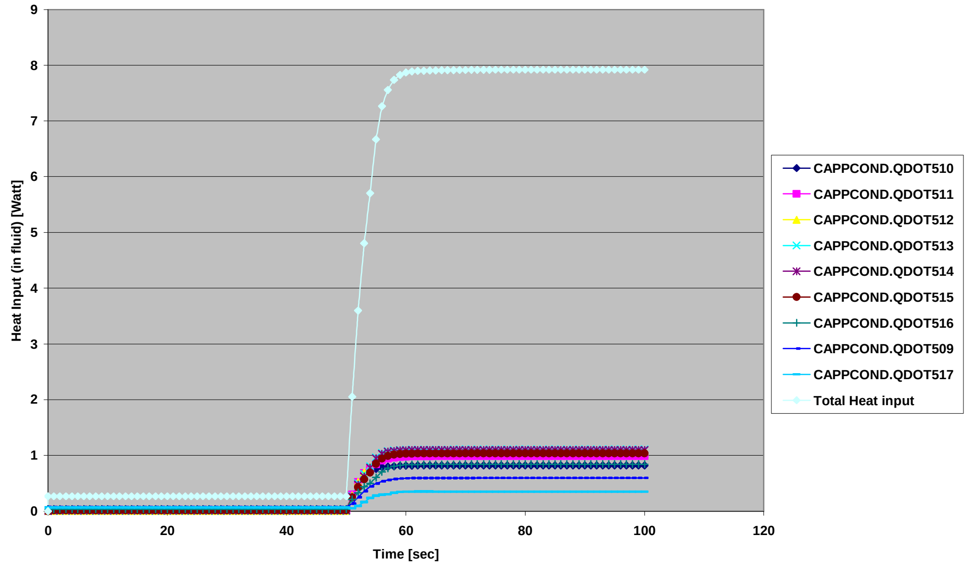


Figure 7-7: Heat input in the CO_2 lumps

The heat in leak through the bolt connections into the base plate is seen in Figure 7-8:

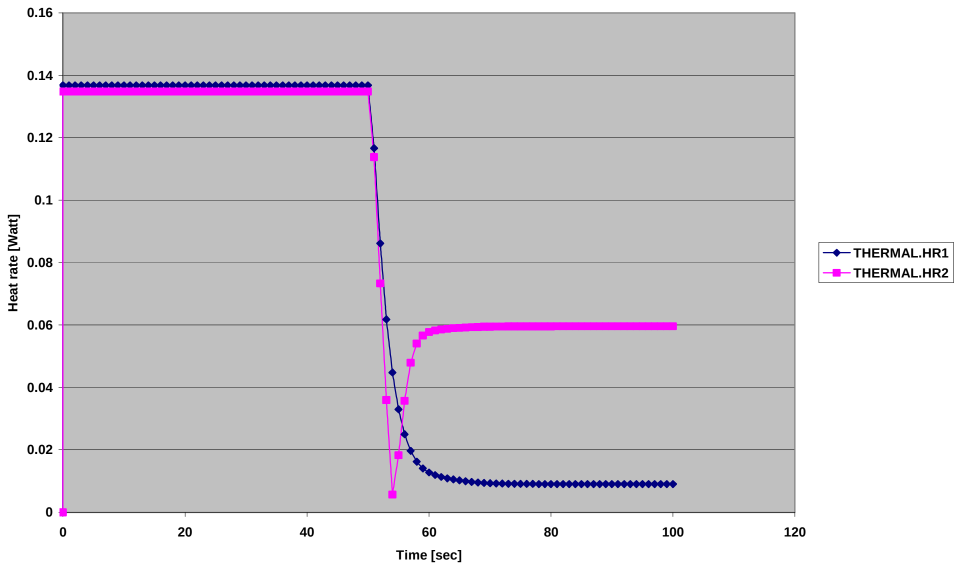


Figure 7-8: Heat input into the base plate

The heat input ratio is calculated in the next table for the t=100 s in the steady state:

Power @ 28 V	
Heat input Heaters	8.0 W
Heat leak to base plate	0.060 + 0.068 = 0.13 W
Heat input in the fluid	7.87 W

From the above it is found that 1.6 % of the total heat input is lost to the base plate at nominal operational case.

Non-operational safety case:

In this section the results of the non-operational safety case are presented and discussed. This case occurs when there is no flow in the loop and the pre-heaters are operating at maximum power. The same thermal model is used as for the normal operation case presented in the previous section. The maximum temperature encountered in the pre-heater is seen in Figure 3-1.

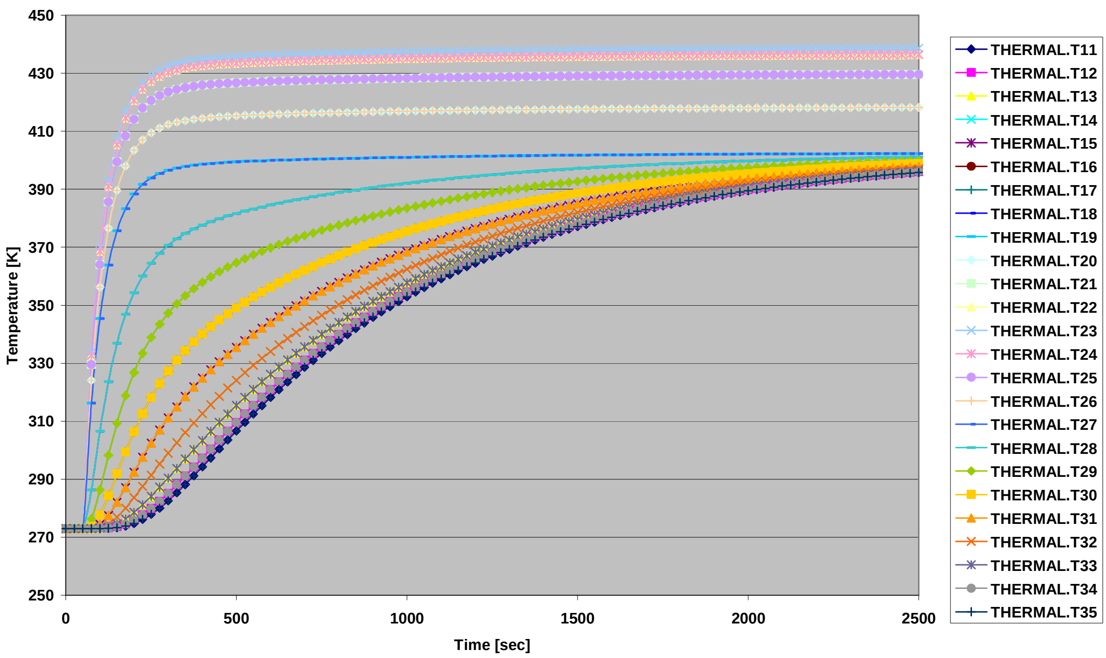


Figure 7-9: Maximum temperature in the pre-heater [K].

From the above figure it's seen that the maximum temperature of 162 °C occurs in the copper structure of the pre-heater.

A better thermal bolt connection between the copper blocks and the base plate can lower the temperature in the pre-heaters, this has a negative effect on the power ratio discussed in the previous section (the heat leak to the base plate @ operation will be higher).

7.1.3 Results summary

In normal operational mode, the pre-heater is able to raise the liquid temperature with 1.72 K. This was determined for the nominal mass flow case with minimal heater power:

- M = 2.0 g/s (Nominal)
- P_{heater} = 8.0 Watt

In the table below the operation performance of the pre-heater is summarized:

Power @ 28 V	
Heat input Heaters	8.0 W
Heat leak to base plate	0.060 + 0.068 = 0.13 W
Heat input in the fluid	7.87 W

The heater control failure mode (safety case) defined as the case where both A and B heaters are switched on at maximum power and a non-running loop. For this case the maximum temperature of **162 °C** occurs in the copper structure of the pre-heater.

7.2 Cold Orbit Heater

7.2.1 Cold Orbit Heater Design

The cold orbit heater properties are as follows:

Function: raise the CO2 temperature to such a temperature that freezing is prevented in the condenser during cold orbits.

Location: The cold orbit heaters are located in the TTCS-boxes after the exit of the heat exchanger and before the split into the Wake and Ram condenser feed lines. The cold orbit section will be located directly on the TTCS base-plate. The location of the cold orbit heater in the box is seen in Figure 7-10.

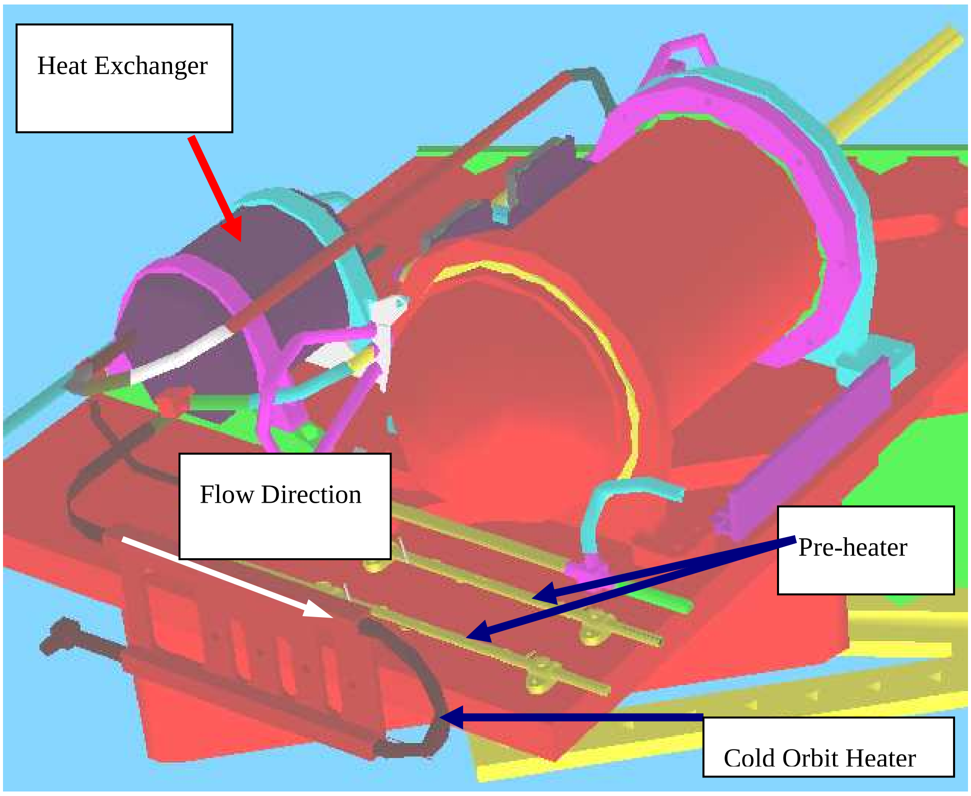


Figure 7-10: Cold Orbit heater location on the base-plate

Heater Design: The cold orbit consists of a copper structure of approx. 5 cm by 12.0 cm. The total heating length is 24.0 cm since the TTCS liquid line passes twice through the cold orbit heater structure. The liquid line from the heat exchanger to the radiators is soldered to this copper structure along the wire heaters. The preliminary design of the cold-orbit heaters is shown in Figure 7-11.

The cold orbit heater is a wire heater soldered onto the cold orbit copper structure. The wire heater has the following properties:

- R = 13.07 Ohm
- $P_{min} = 26.5^2/13.07 = 53.72$ Watt
- $P_{min} = 28^2/13.07 = 60.00$ Watt
- $P_{min} = 29.5^2/13.07 = 66.6$ Watt

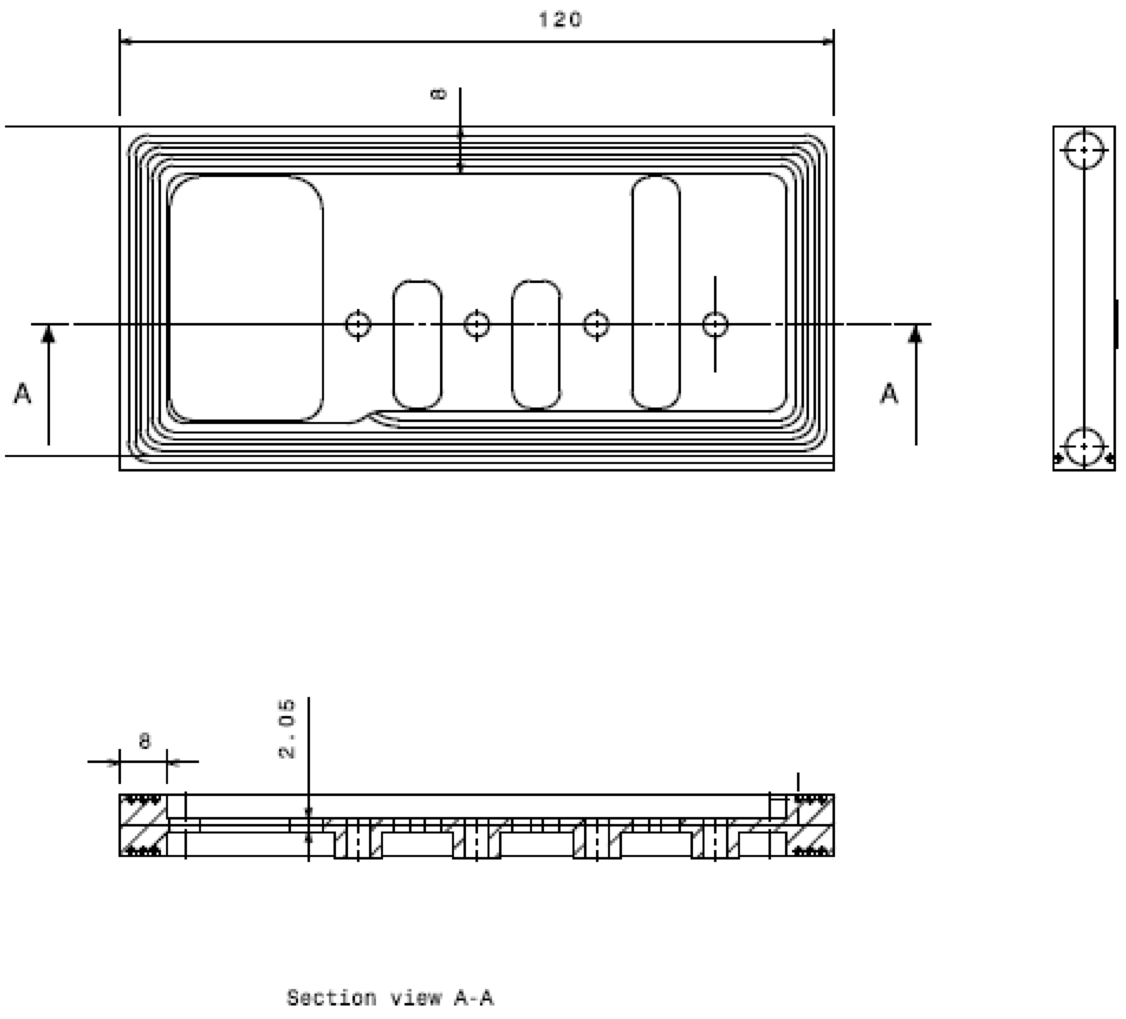


Figure 7-11: Cold Orbit Heater Design

7.2.2 Cold Orbit Heater Model

The purpose of the thermal model is check whether the length of the heated cold orbit heaters section is sufficient to heat the CO_2 liquid with 60 watt heat input. A second goal of the present model is to determine the maximum temperature at heater control failure.

The cold orbit model is implemented in Sinda/Fluint. The thermal model divides the cold orbit tubing in twelve heated sections.

In the present study the cold orbit heater is part of a small liquid loop, seen in Figure 7-12. In this small loop it's quit easy to set the cold orbit ingoing temperature T_{in} and the saturation temperature set point $T_{set\ point}$. The cold orbit heater is modelled as a heat exchanger seen in Figure 7-12 as HX-3.

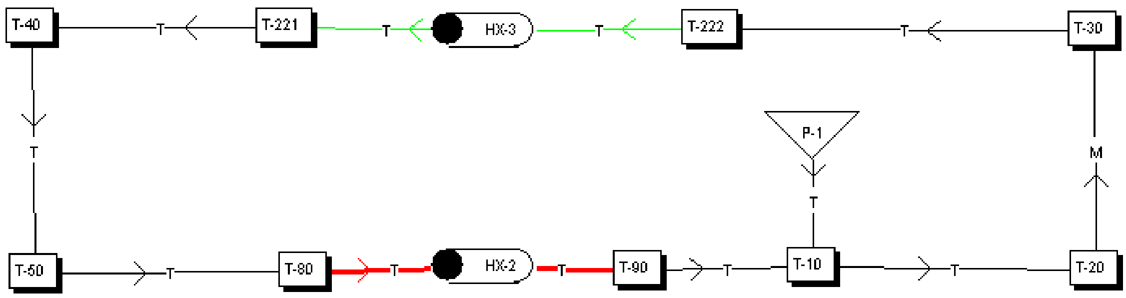


Figure 7-12: Small fluid loop with cold orbit heater (HX-3)

The fluid part of the heat exchanger (cold orbit heater) is seen in

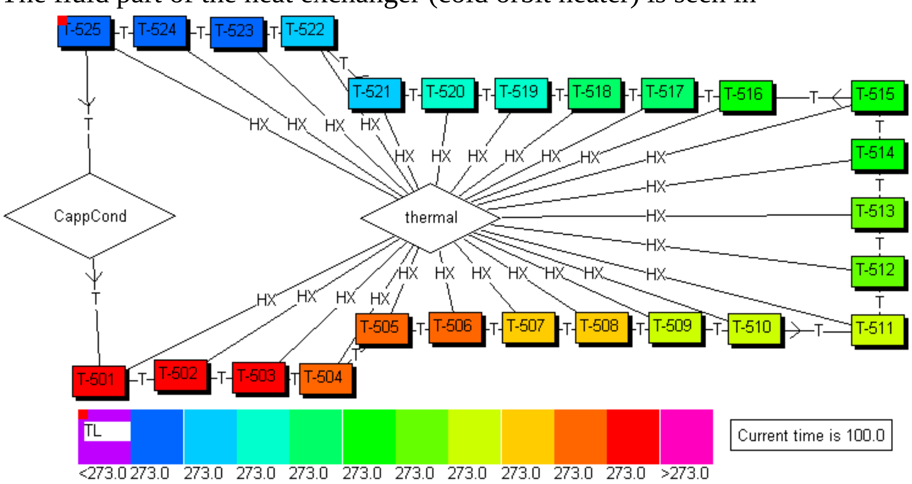
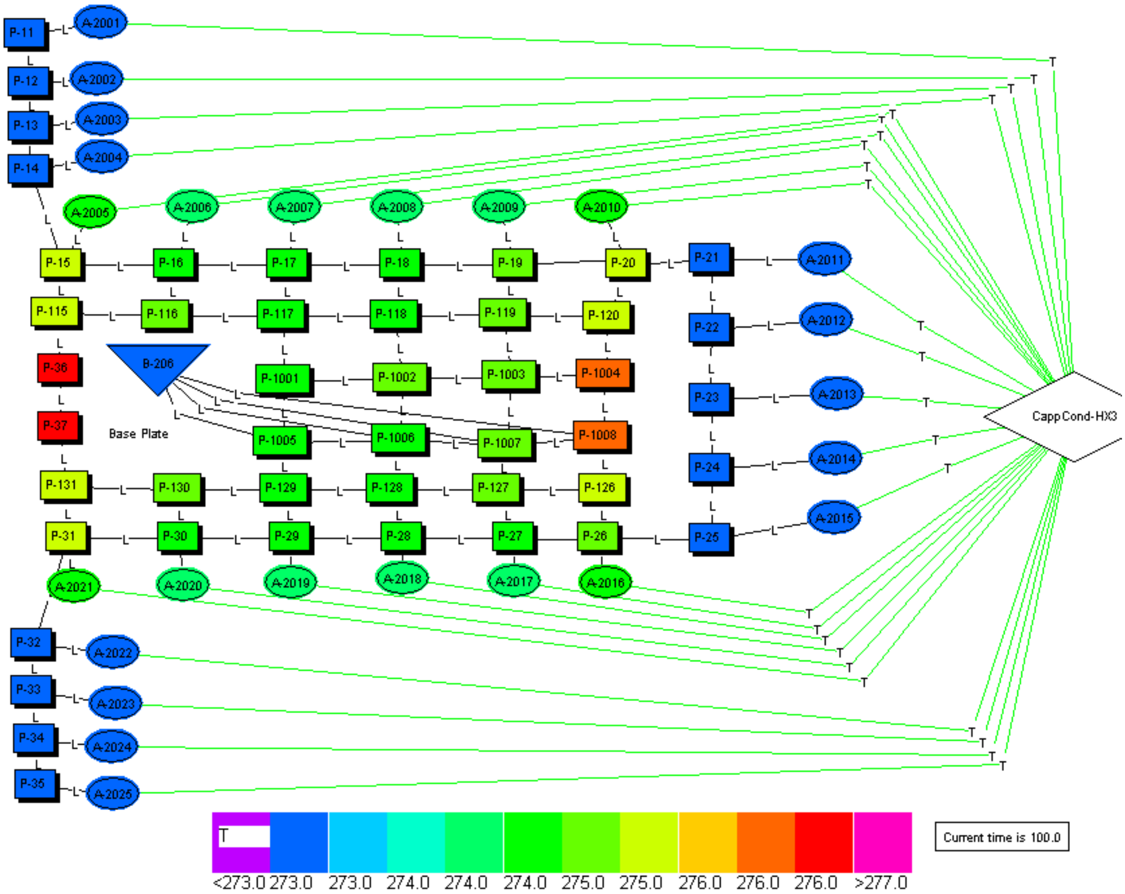


Figure 7-13: Cold Orbit Heater fluid network

The thermal part of the cold orbit heater model (tube nodes, copper nodes and the connections to the base plate) is seen in



The cold orbit heater connected with the base plate, which is modelled as a thermal boundary node (B-206) having a constant temperature of 273 K. The connections between the copper blocks and the base plate are estimated having the thermal conductivity of 0.13 [W/K]. The estimation of the conductivity through the connection between the cold orbit heater structure and the base plate is seen in Appendix B.

Operational Case

In this section the operational case is discussed and the results are presented. The main objective is to quantify the ratio between the heat input in the fluid and the heat loss to the base plate. The temperatures in the lump before and after the cold orbit heater section are shown in Figure 7-14 for the nominal mass flow and minimal heater power:

- m = 4.0 g/s (Nominal)
- P_{heater} = 60.0 Watt

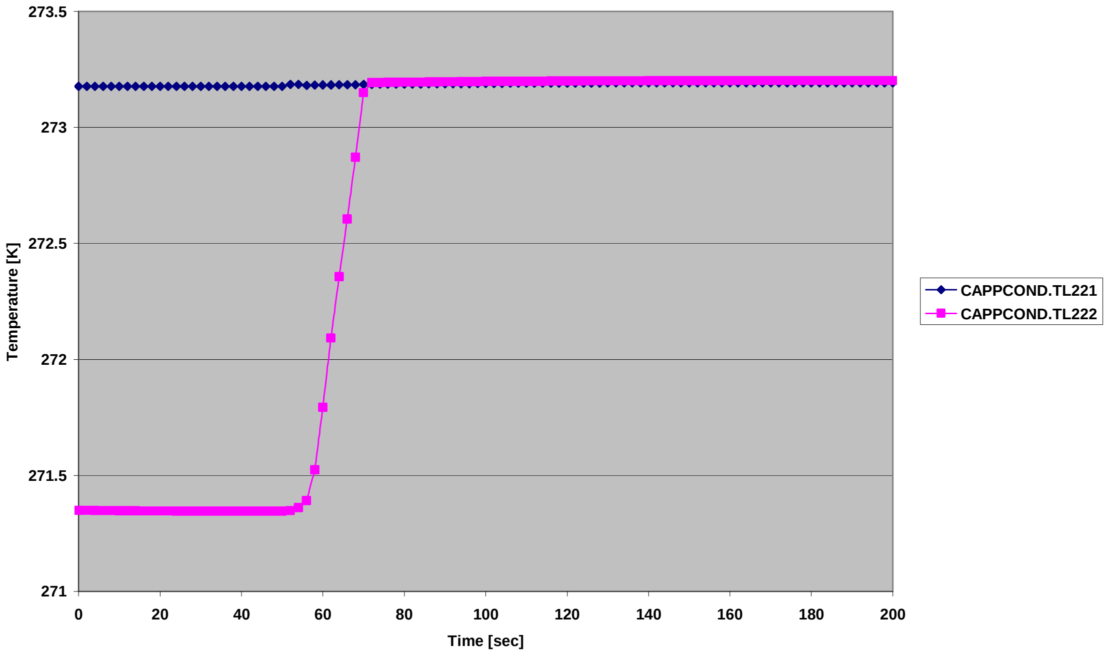


Figure 7-14: Temperature before (TL222) and after (TL221) the cold orbit heaters during TTCS operation.

It is seen that the cold orbit heater is able to raise the liquid temperature up to the saturation temperature (273.15 K). In Figure 7-15 the vapour quality of the fluid is seen before and after the cold orbit section.

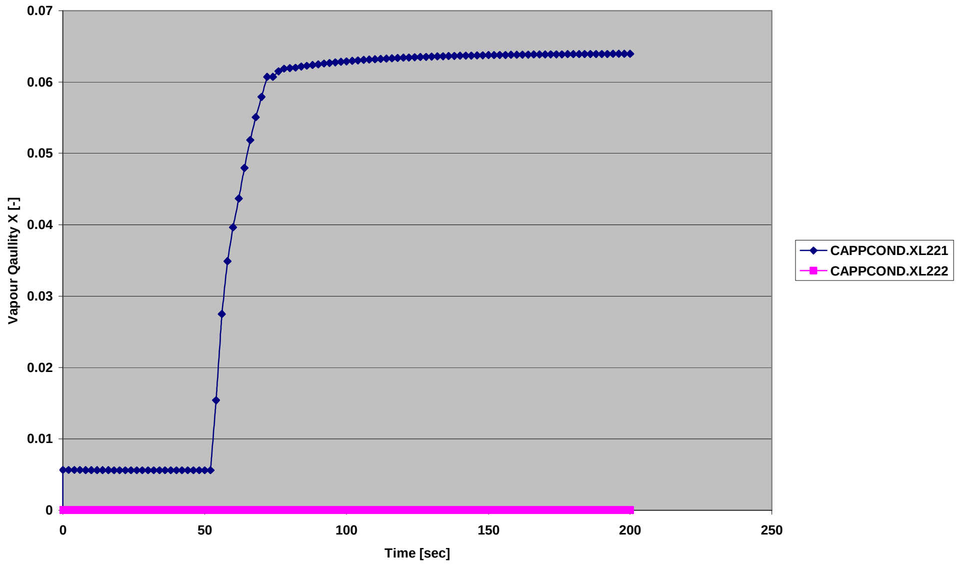


Figure 7-15: Change in vapour quality before (XL222) and after the cold orbit heater (XL221).

The heat input in the liquid lumps is seen in Figure 7-16.

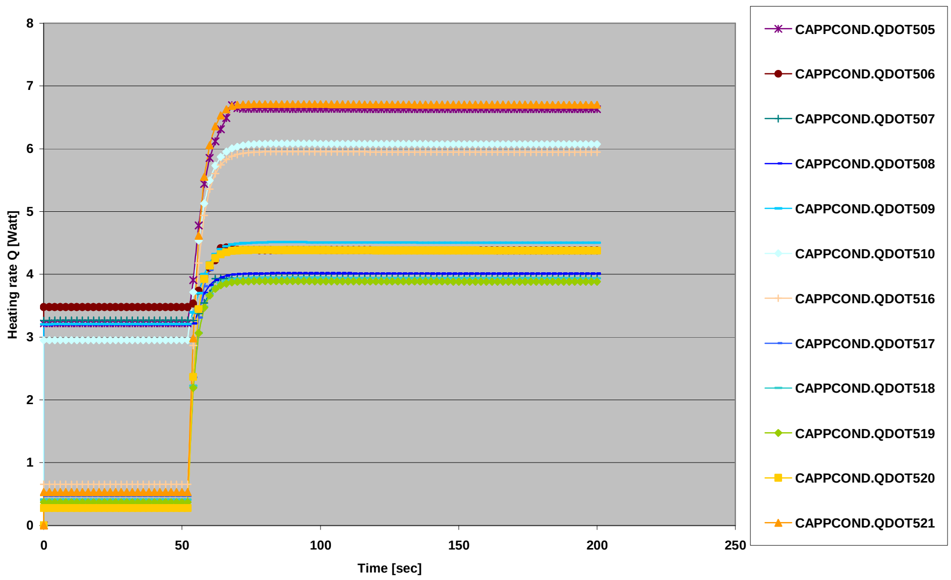


Figure 7-16: Heat Input in the CO_2

The heat input through the bolt connections into the base plate is seen

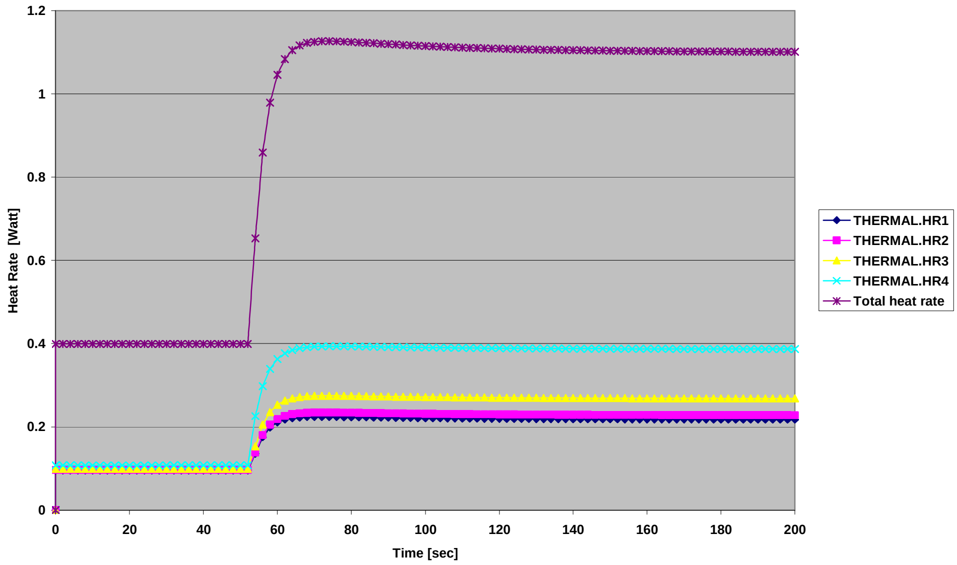


Figure 7-17: Heat input into the base plate.

The heat input ratio is calculated in the next table for t=200 sec in the steady state:

Power @ 28 V	
Heat input Heaters	60.0 Watt
Heat leak to base plate	1.10 Watt
Heat input in the fluid	58.9 Watt

From the above it is found that 1.8 % of the total heat input is lost to the base plate at nominal operational case.

Non-operational safety case:

In this section the results of the non-operational safety case are presented and discussed. This case occur when there is no flow in the loop (non-operating loop) and the cold orbit heaters A and B are operating at maximum power resulting in a power input of 120 Watt in the cold orbit heaters structure. The maximum temperatures encountered in the cold orbit heater is seen in

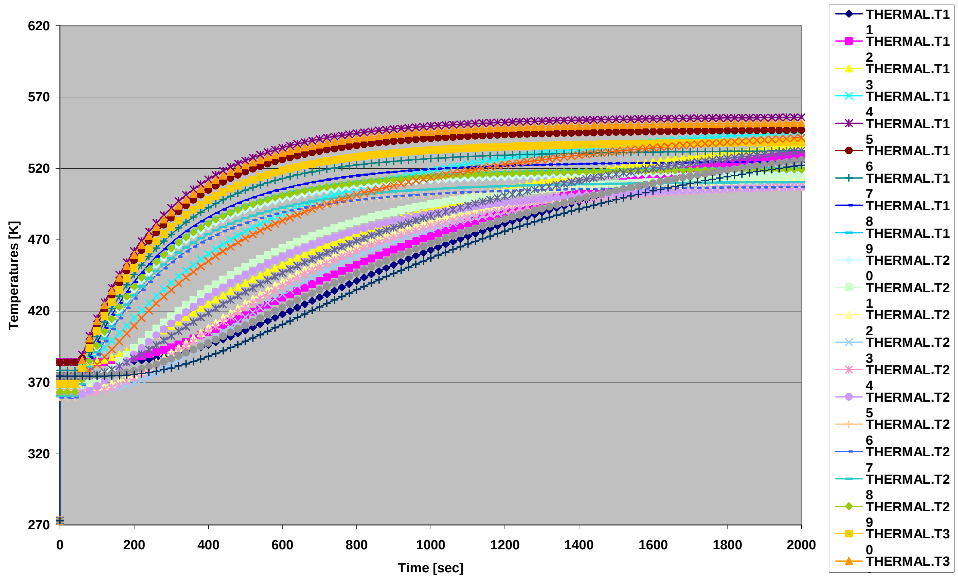


Figure 7-18: Maximum temperature in the cold orbit heater.

From the above figure it’s seen that the maximum temperature of 555 [K] or 281 [°C] occurs in the in the copper structure of the cold orbit heater.

A bolt connection with higher conductivity results in lower maximum temperatures in the cold orbit heaters; this has a negative effect on the power ratio discussed in the previous section. This would result in an increasing heat leak to the base plate during operation.

7.2.3 Results summary

In normal operational mode, the cold orbit heater is able to raise the liquid temperature up to the saturation temperature (273.15 K) and was able to conduct most of the heater power into the CO_2. This was determined for the nominal mass flow case with minimal heater power:

- M = 4.0 g/s (Nominal)
- P_{heater} = 60.0 Watt

In the table below the performance of the pre-heater is summarized:

Power @ 28 V	
Heat input Heaters	60.0 Watt
Heat leak to base plate	1.10 Watt
Heat input in the fluid	58.9 Watt

The heater control failure mode (safety case) defined as the case where both A and B heaters are switched on at maximum power (total power of 120 watt) and a non-running loop. For this case the maximum temperature of **555 [K] or 281 [°C]** occurs in the in the copper structure of the cold orbit heater.

7.3 Start-up heater on the heat exchanger

The start-up heater properties are summarized as follows:

Function: The objective of the start-up heaters is to raise the TTCS liquid flow from – 40 °C to – 20 °C during start-up and cold orbit operation.

Location: The start-up heaters are wire heaters connected to the large thermal mass of the TTCS heat exchanger as seen in Figure 7-19.

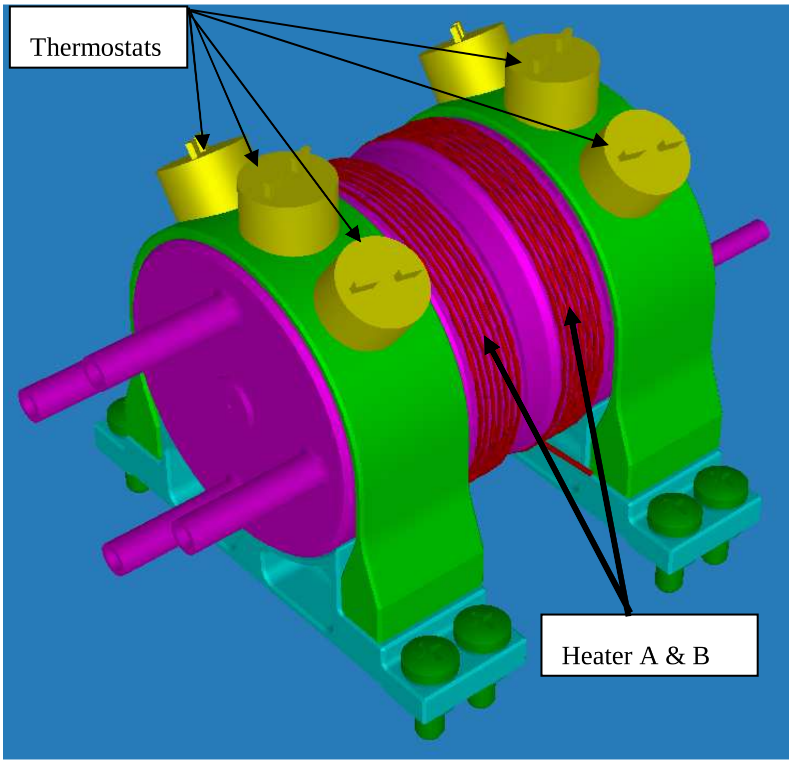


Figure 7-19: Thermostat and wire heaters placement onto the TTCS heat exchanger

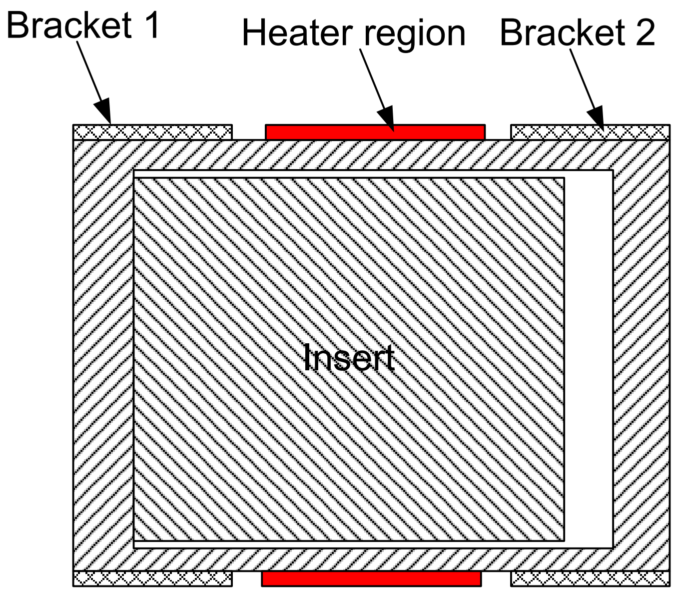
Heater Design: The start-up heater is a wire heater soldered onto heat exchanger of the TTCS, with the following properties:

- R = 14.05 Ohms
- P_{min} = 26.5^2/14.05 = 50.0 Watt
- P_{nom} = 28.0^2/14.05 = 55.8 Watt
- P_{max} = 29.5^2/14.05 = 61.9 Watt

The heat exchange is equipped with three thermostats on each wire heater (A and B, main and redundant wire heater). These thermostats have a set point of 80[°C].

7.3.1 Heat Exchanger model

The purpose of the current heat exchanger model is to calculate the maximum temperatures at heater control failure. This is the case where both heaters (A and B) are switched on resulting in a total power input of 100 [Watt].



The model presented in this section is implemented in Thermal Desktop. The thermal conductivities between the HX outer surface and the bracket surfaces are based on the mechanical design and pressures between the brackets (bolt forces):

	Bolt type	bracket pressure [Mpa]	Contact Conductance [W/m^2 K]	
Bracket 1	RVS 316	2.04	≈5000	Top side
		10.18	≈5000	Bottom side
	In 718	2.48	≈5000	Top side
		12.39	≈5000	Bottom side
Bracket 2	RVS 316	0.204	≈500	Top side
		1.018	≈500	Bottom side
	In 718	0.248	≈500	Top side
		1.239	≈500	Bottom side

The thermal conductivity through the connection between the heat exchanger bracket and the base plate is based on the pressure in the bolts:

Bolt Material	Bolt Force [N]	Contact Pressure [Mpa]	Contact Conductance [W/m^2 K]
RVS 316	541.8	12	≈5000
In 718	2956.3	67.1	≈5000

The total conductivity between the brackets and the base plate (0.132 [W/K]) is calculated and presented in **Appendix C.**

The model of the heat exchanger built in Thermal Desktop is seen in Figure 7-20 Figure 7-21.

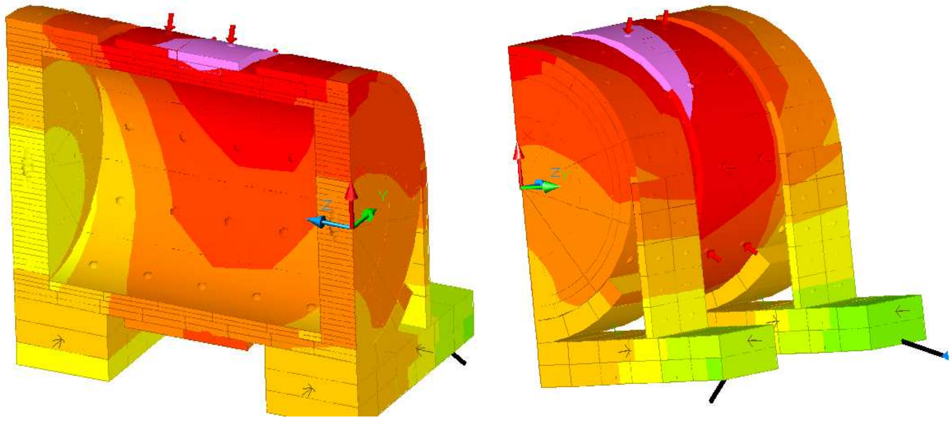


Figure 7-20: Front and backside view of the heat exchanger model (Without insert)

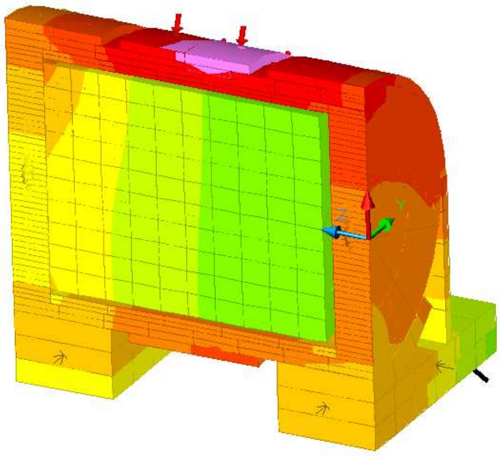


Figure 7-21: Front view of the heat exchanger model (With insert)

The resulting temperature evolution is seen

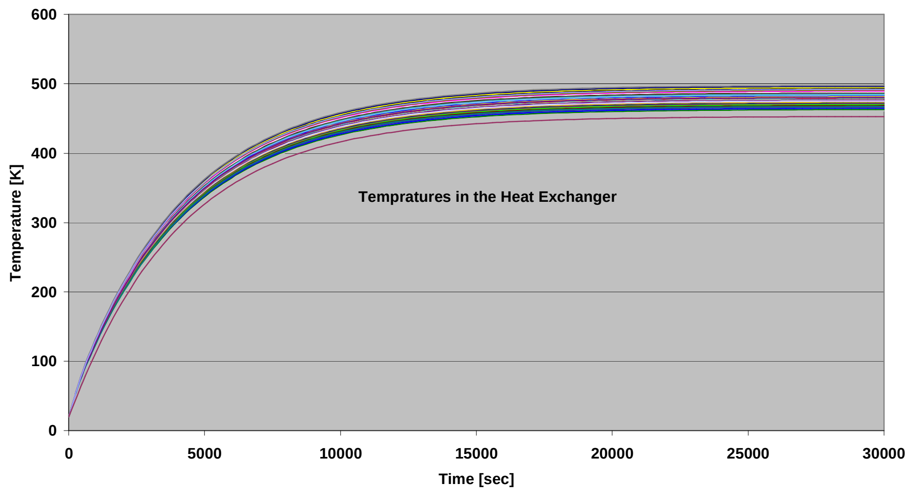


Figure 7-22: The temperature distribution in the heat exchanger @ heater control failure.

The maximum temperature of **475 [K] or 201 [°C]** occurs in the in the outer surface of the heat exchanger.

Due to structural limitations, the heat exchanger is equipped with thermostats having a set point of +80 °C. The temperature distribution in the heat exchanger is seen in Figure 7-23 at approx. a switching point of the thermostats (100 °C) with a margin of 20 degrees with respect to the worst case.

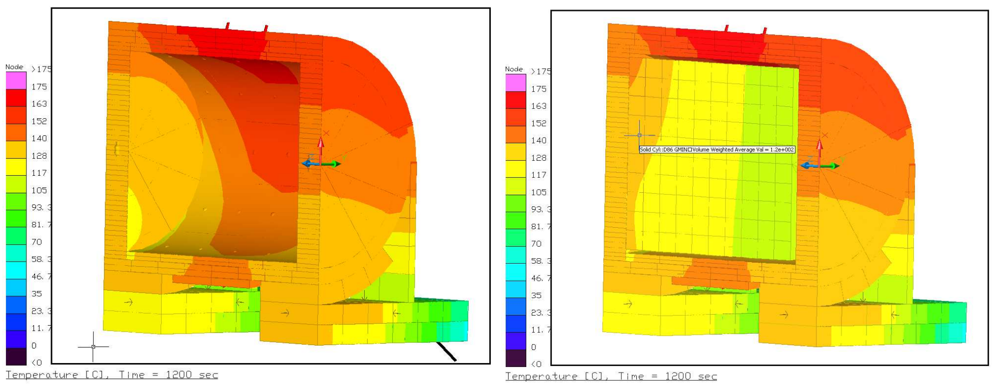


Figure 7-23: Temperature distribution in the heat exchanger @ thermostats switching point.

7.4 Radiator capillary feed and return lines heaters

The liquid line heater properties are as follows:

Function: The objective of the TTCS liquid line heaters is to defrost the TTCS CO_2 condenser lines after an AMS complete power down.

Location: The heaters are soldered onto the TTCS capillary tubing running from the manifold to the condensers.

Heater design: The liquid line heaters are wire heaters soldered onto the capillary Inconel tubes from the manifolds to the condensers, for more detailed description the reader is referred to the TTCS Heater Specification document "AMSTR-NLR-TN-043".

To minimize heat leak from the liquid lines wire heaters to the condenser plate a foil heaters are placed onto the condenser plate. The wire/foil heaters have the following properties:

- Wire heaters (per heater):
    - R = 503 Ohms
    - P_{min} = 0.758 Watt
    - P_{nom} = 0.846 Watt
    - P_{max} = 0.939 Watt
- Foil heater (condenser plate):
    - R = 12.8 Ohms
    - P_{min} = 3.77 Watt
    - P_{nom} = 4.21 Watt
    - P_{max} = 4.68 Watt

The structural layout of the capillary liquid lines with manifold and brackets is seen in Figure 7-24. A detailed picture of the capillary lines brackets is seen in Figure 7-25

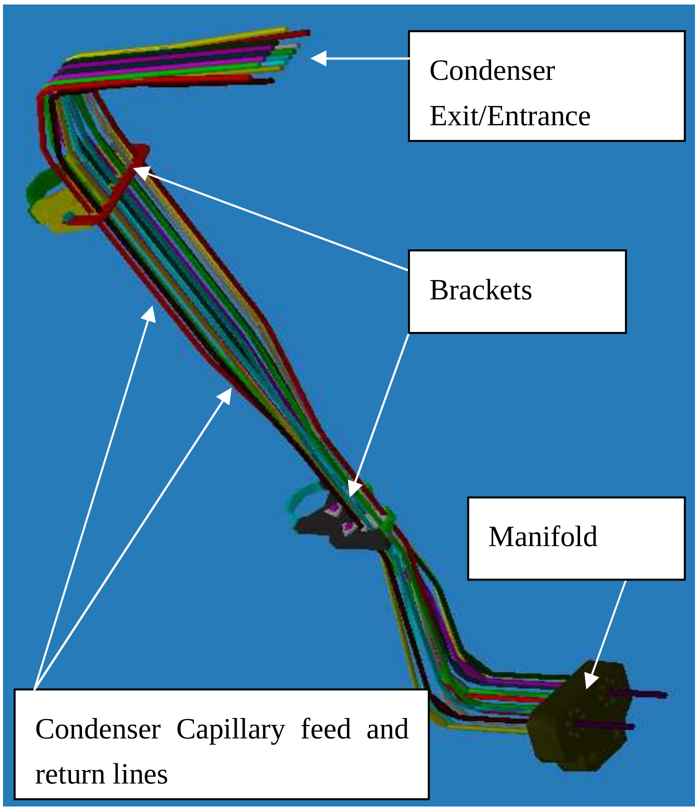


Figure 7-24: Capillary liquid lines layout

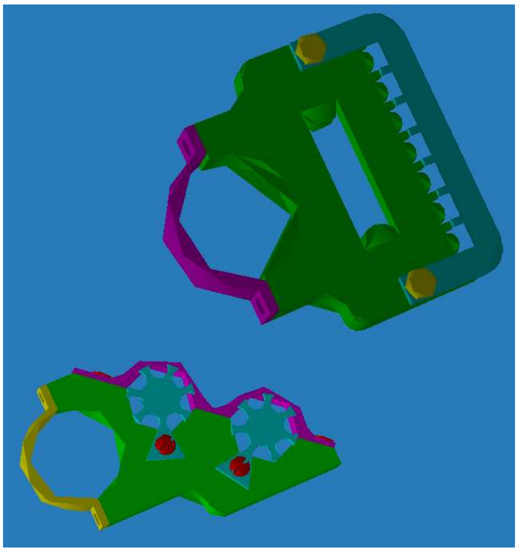


Figure 7-25: Capillary liquid lines brackets.

The maximum temperature occurring in the capillary liquid line is calculated based on the following assumptions:

1. The bundle of liquid lines is placed in Multi Layer insulation.
2. It is assumed that the all the heat is exchanged with the environment through radiation. (Worse case, no heat leak through conduction).

The layout with insulation is seen in Figure 7-26.

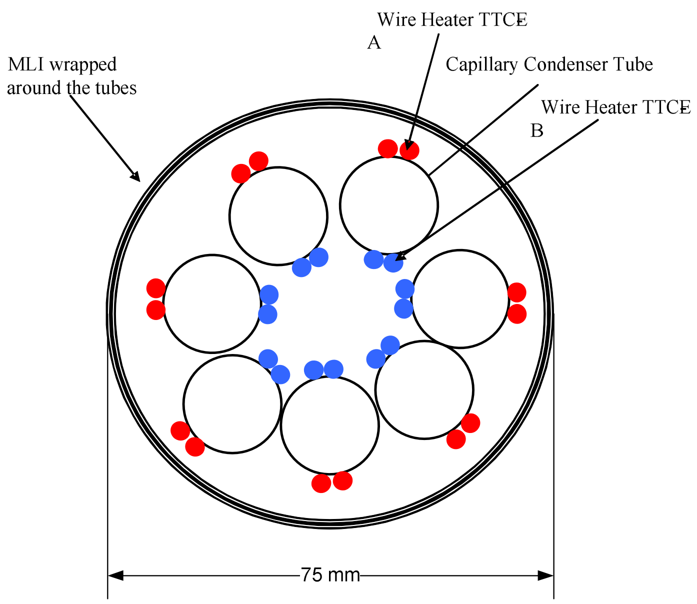


Figure 7-26: Capillary liquid line heaters with MLI insulation

The MLI sheets (4x) are wrapped around the bundle of capillary liquid lines. For the high evacuated MLI system (multiple surfaces) the theoretical effective emissivity, ε_{eff}, for a blanket of N isolated surfaces, or layers of emissivity of ε_1 and ε_2 on opposite sides, is computed as

$$\varepsilon_{eff} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_1} - 1} \cdot \left(\frac{1}{N+1} \right)$$

$$\varepsilon_1 = \varepsilon_2 = 0.05$$

$$N = 3$$

$$\varepsilon_{eff} = 6.41 \times 10^{-3}$$

The maximum temperature occurring in the capillary liquid lines is found to be 301 [°C] and is calculated as follows:

TTCS Liquid Line Heaters Sizing

Maximum temperature at hot condition:

$D_{oMLI} := 75 \cdot mm$ Outer diameter MLI

$L_1 := 0.77 \cdot m$ Lenght Tubing and MLI

$A1 := 2 \cdot \pi \cdot D_{oMLI} \cdot L_1$ $A1 = 3.629 \times 10^5\, mm^2$

$\sigma := 5.6 \times 10^{-8} \cdot \frac{W}{m^2 \cdot K^4}$

$\varepsilon_{IR} := 0.05$ Effective emissivity

$N1 := 3$ Number of MLI sheets

$\varepsilon_{eff} := \frac{1}{\frac{2-\varepsilon_{IR}}{\varepsilon_{IR}}} \cdot \left(\frac{1}{N1+1}\right)$ $\varepsilon_{eff} = 6.41 \times 10^{-3}$ MLI system effective emissivity

$Tenv := 303\, K$ Environmet Temperature

$P_{LLheaters} := 13.15\, W$ Total heaters power

$T_b := \left(Tenv^4 + \frac{P_{LLheaters}}{\sigma \cdot A1 \cdot \varepsilon_{eff}}\right)^{0.25}$ Tube temperature

$T_b = 575.094\, K$ $T_b = 301.944\, °C$

7.4.1 Results summary

The maximum temperature occurring in the capillary liquid lines is found to be **301 [°C]** in heater control failure mode (safety case).

7.5 Oscillating heat pipe (OHP heaters)

This section describes the Oscillating Heat Pipe (OHP) experiment. It gives an overview of the experiment. The focus is mainly on thermal and safety aspects.

The Oscillating Heat Pipe heater properties are as follows:

Function: The objective of the OHP heater is to operate the OHP experiment. When the OHP heater is operated the heat is conducted by the OHP and dumped in the CO_2 AMS02 TTCS Primary Loop. The design of the AMS OHP is found in document "*TTCS Oscillating Heat Pipe Design Description*" AMSTR-NLR-TN-037.

Location: The wire heaters are soldered onto an L-shaped copper structure as seen in Figure 7-27.

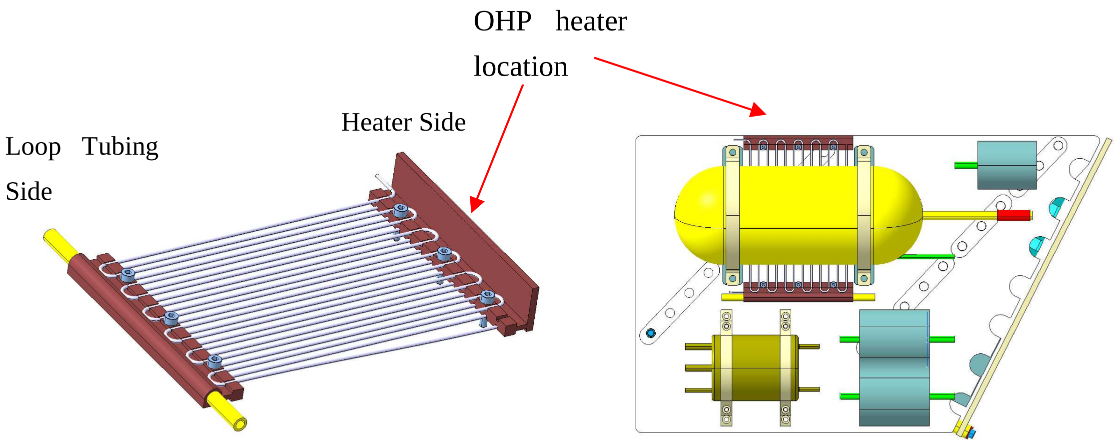


Figure 7-27: AMS02 OHP experiment design layout.

Heater design: The wire heater has the following properties:

- R = 15.7 Ohms
- $P_{min} = 26.5^2/15.7 = 44.7$ Watt
- $P_{nom} = 28.0^2/15.7 = 50.0$ Watt
- $P_{max} = 29.5^2/15.7 = 55.4$ Watt

The safety issues concerning the OHP experiment are:

- The maximum design pressure in the OHP tubing at heater control failure (heater switch on).
- The maximum temperature occurring at the condenser side (TTCS CO_2 tubing) is to be determined.

7.5.1 OHP thermal model

The purpose of the current OHP thermal model is the determination of the maximum temperatures occurring in the OHP structure at heater control failure.

Model description:

- OHP tubing: L = 3279.15 mm, D_{in} = 1.2 mm, D_{out} = 1.5 mm
- Conductive link between the evaporator (heater) copper structure and the base plate: G_{BP1} = 0.9 W/K.
- Conductive link between the condenser copper structure and the base plate: G_{BP2} = 0.195 W/K.

The model layout is seen in Figure 7-28 while the physical model is seen in Figure 7-29.

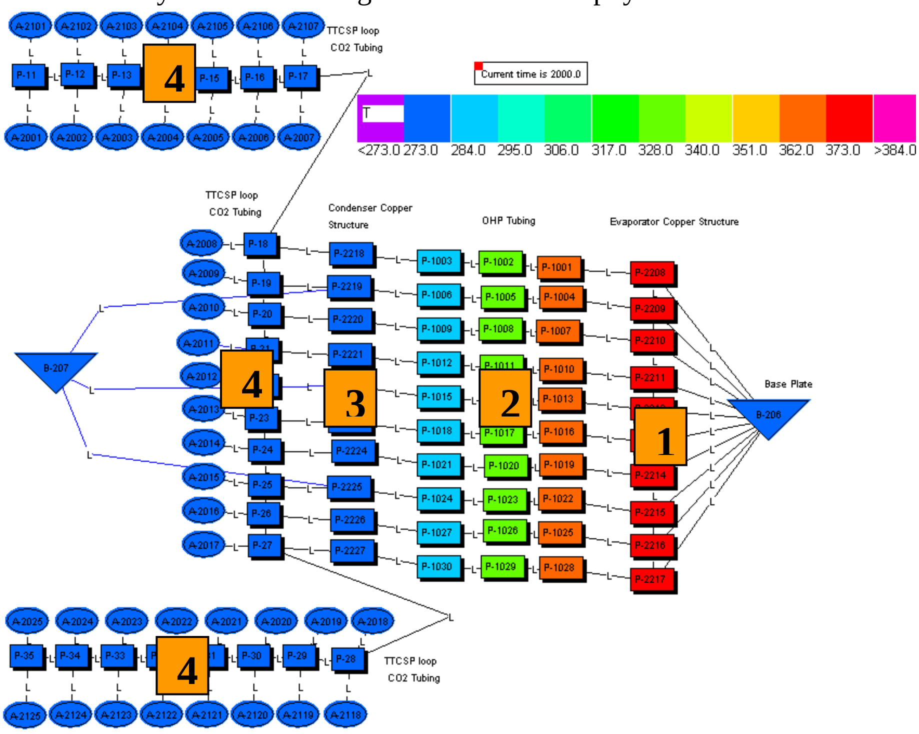


Figure 7-28: AMS 02 OHM experiment (thermal model layout)

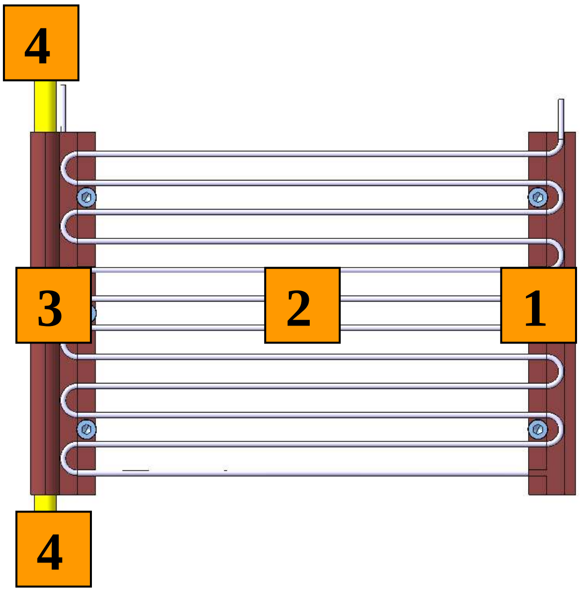


Figure 7-29: ASM02 OHP experiment layout

The OHP design has the following properties:

- The volume of the containing tubing is 2.26 ml FC-87.
- The fill charge will be 70 % resulting in a total mass of 2.56 gram FC-87 @ 290 K.
- FC-87 Properties:
    - Critical temperature: 423 K (150 °C)
    - Critical pressure: 21.3 bar
    - Liquid density: 1650 kg/m^3 @ 298 K
    - Liquid specific heat: 1100 J/kgK @ 298 K

The P-T curve of FC-87 is seen in Figure 7-30. Assuming an OHP maximum average design temperature of 100 °C (273.15 K), the MDP (maximum design pressure) is 8.94 Bar.Figure 7-30: P-T curve FC-87

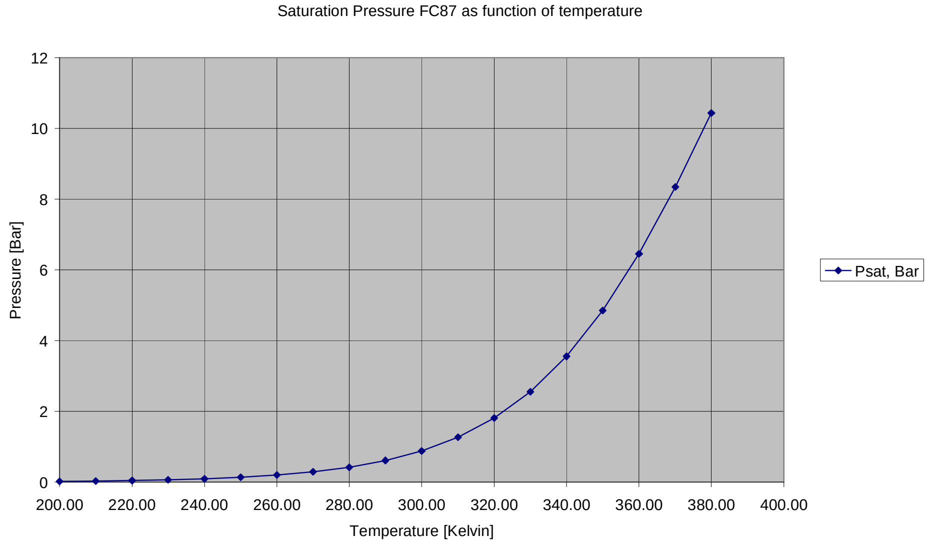


Figure 7-30: P-T curve FC-87

Based on the MDP of 8.94 bars the proof and burst pressure are as follows:

Maximum Design Pressure	8.94 Bar
Proof Pressure (1.5xMDP)	13.4 Bar
Burst Pressure (4.0xMDP)	35.7 Bar

Table 7-1: OHP Design pressures.

The design verification comprises:

- Fill accuracy will be measured according TBD procedure to secure MDP
- The OHP will be pinched and welded and X-rayed
- Proof pressures verification by test

The calculation of the maximum stresses in the material is calculated and presented in Appendix D. The limiting Von Mises stress is:

σ_{VM} = 1.987 MPa

With a safety factor, the material should have a yield stress larger than:

SF = 4.0 SF: Safety factor

$\sigma_{yieldlimit} = SF * \sigma_{VM} =$ 7.95 MPa

This calculation shows that all materials with a yield stress above the yield limit can be used. The tube material for the OHP is stainless steel with a minimum yield stress of 195 MPa. Therefore all stresses in the material will be acceptable (If the maximum temperature in the OHP stays below 100 °C).

316L stainless steel has a yield strength of 234 Mpa (source: Perry chemicals engineers handbook sixth edition table 23-10 p23-43) and easily fulfils the yield stress limit.

The resulting safety case temperature evolution, by modelling, in the OHP is seen in Figure 7-31.

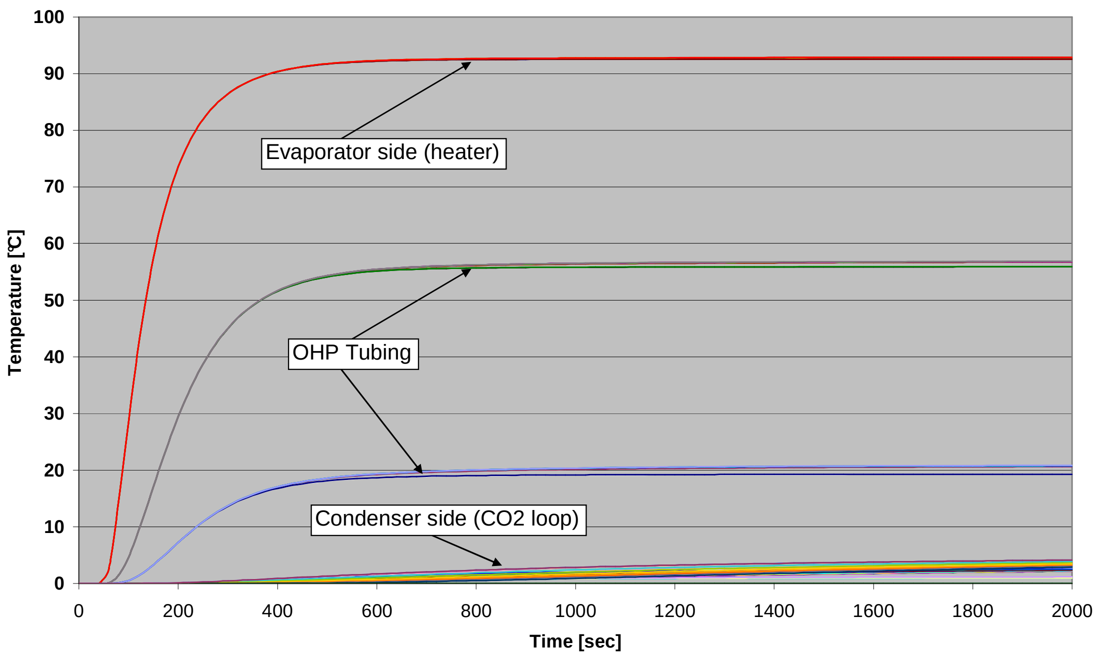


Figure 7-31: OHP Maximum temperatures @ safety case.

From the above figure it's seen that the maximum temperature of **93 [°C]** occurs in the in the copper structure on the evaporator side of the OHP. It's clear that the OHP tubing stays below the maximum design temperature of **100 [°C]** and thus below the Maximum Design pressure.

The maximum temperature on the condenser side (CO_2 loop) is seen to be below the **10 [°C]**.

7.5.2 Results summary

The OHP heater failure mode (safety case) results in a maximum temperature of **93 [°C]** in the copper structure on the evaporator side of the Oscillating Heat Pipe. The maximum temperature in the Oscillating Heat Pipe (60 °C) stays below the maximum design temperature of 100 [°C] and thus the pressure in the OHP stays below the MDP of 8.94 [Bar].
The maximum temperature on the condenser side (CO_2 loop) is below the **10 [°C]**.

7.6 Accumulator heaters

The accumulator heaters safety assessment (by modelling) is performed by SYSU and presented in |TTCS-SYSU-AN-001-2.0 “TTCS Accumulator Safety Analysis”.

7.6.1 Peltier elements

Peltier elements properties:

- Melcor CP 1.0 – 127 – 05 L 2 series
- Power supply 11.5 VDC
- PI conrol
- P_{max}

The Peltier elements are used to cool the accumulator. They are used to lower the set point temperature, based on the ground command. The Peltiers can produce Joule heat, however, depending on the working current. Worst case is when the Peltier elements are operating and the TTCS pump is not running, e.g. before starting up. In that case the (Joule) heat can not be carried away by the loop and the Peltier elements will heat the accumulator.
The detailed analyses on this case can also be found in TTCS-SYSU-AN-001-2.0 “TTCS Accumulator Safety Analysis”

7.7 Tracker condenser heaters

The condensers heaters safety assessment (by modelling) is performed by SYSU. The maximum condenser temperature without pumped CO_2 is -5 °C. The detailed analysis will be presented in TTCS-SYSU-SIMU-PR-002-2.0 “TTCS Thermal Analysis and design report”.

7.8 Tracker evaporators

The tracker evaporators safety assessment (by modelling) is performed by SYSU and can be found in TTCS-SYSU-SIMU-PR-002-1.0 “TTCS Thermal Analysis and design report”. The maximum temperature of the evaporator environment is lower then 30 °C (Figure 7-4 on page 82). Analyses for an operating Tracker without TTCS cooling are still to be made.

7.9 Results summary

In the table below the maximum temperatures for the various heated components evaluated in this document are summarized:

TTCS Components	Maximum Temperature Safety case [°C]
Pre-heater	162
Cold Orbit Heater	281
Start-up heater	301
Oscillating heat pipe	93

Table 7-2: TTCS heated components not thermostat protected

Remark: The maximum evaporator temperature is still to be determined. However in the final analyses in section 8 the temperature is assumed to be infinite (approach 1) or 100 °C (approach 2).

8 Outline safety approach principle

The goal of the safety approach is to set a procedure to show that in all cases the maximum design pressure is not exceeded.
In the design phase of the loop the design pressure was directly determined by the fill ratio and the overall maximum design temperature. The maximum design pressure was fixed at 160 bars at a maximum temperature (on earth) of 65 °C and a density (fill ratio) of 592 g/l.

Two safety approaches are presented in the following two sections:

1. The first approach takes as an assumption that the heated non thermostat protected components don't contain any liquid/vapour (infinitely hot) (worse case). Then the maximum allowable temperature for the unheated sections as function of T_{accu} is calculated such that the pressure in the loop is equal 160 bars. The corresponding $T_{unheated}$ section is used as Maximum Design Temperature (MDT) for the rest of the loop.
2. In the second approach an extreme temperature for "over"-heated parts is assumed (due to failure of heaters) e.g. 445 °C.

For both approaches the TTCS loop is divided into three component groups:

1. Unheated components of the loop, these are the components where no heaters are placed and where the temperature can be assumed to be constant with a non-operating loop.
2. The second group consist of the three components which are equipped with thermostats:
   - Accumulator; TS = +55 °C for HP heaters, $T_{env} < T_{TS}$
   - Accumulator; TS = +45 °C for Peltier Elements, $T_{env} < T_{TS}$
   - Heat exchanger; TS = +80 °C, $T_{env} < T_{TS}$
   - Condensers; TS = -35 °C, $T_{env} < -5$ °C

   It is assumed that these components never exceed the switching temperatures of the thermostats (accumulator will not exceed +45 °C). This acceptable for safety since these components are three fold protected with three thermostats each.
   The maximum temperature of the condensers is not based on the switching temperature of the thermostats but on modelling results (interaction with environment). The temperature of the condensers without pumped CO_2 is always below – 5 °C.
3. The Heated Elements in the TTCS Loop without thermostats.
   The maximum temperatures in these components were determined in the previous chapter (chapter 5).

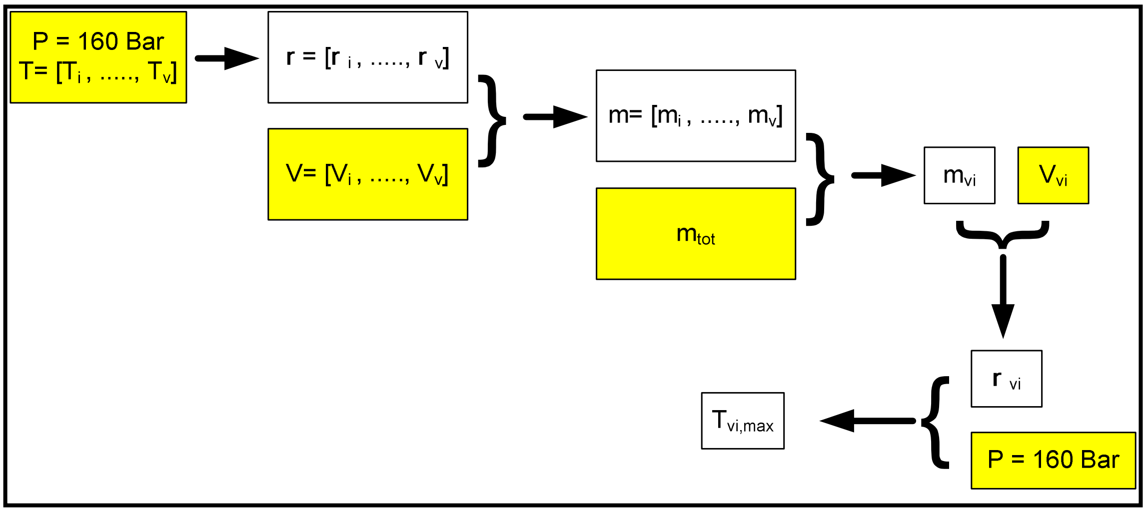
8.1 Max. Allowable temperature determination

As stated before the loop is divided in several sections (volumes):

i. Capillary Condenser Lines
ii. Accumulator
iii. Heat Exchanger
iv. ....
v. .....
vi. Unheated components.

The following is assumed:

1. Max Pressure in the loop: P = 160 Bar
2. Total CO_2 mass: m_{tot} = 740.4 gram
3. Temperature Components: T_{ii} , T_{iii}, ..., T_{vi}
   The temperatures in the different heated components result either from thermal analysis or the set point of the thermostats.
4. Volumes Components: V_i, V_{ii} , V_{iii} ,.....V_{vi}



8.2 First Approach

In this approach the following assumptions are made:

- Condensers are thermostat protected and can not exceed the temperature of -5 [°C].
- Heat exchanger is thermostat protected and can not exceed the temperatures of respectively [80, 90, and 100] [°C]. These three temperatures are chosen to study the effect of the heat exchanger thermostats temperature set point on the overall allowable temperature increase in the unheated components.
- It is assumed that the heated components don’t contain any fluid (liquid and/or gas) (very high temperatures thus very low density).
- An accumulator temperature is assumed varying from 50 °C to 59 °C.

The maximum allowable temperature in the unheated components is calculated such that the pressure in the system, under the above described conditions, is equal to the maximum allowable design pressure of 160 [Bar].

Three calculations are performed with three different assumed heat exchanger temperatures [80, 90, and 100] [°C]. The assumed loop temperatures and the resulting densities and CO_2 mass in the different components are listed in

Component	Volume [ml]	Temperature [°C]	Density [g/l]	Mass [g]
RAM & WAKE cap condenser lines	43.4	-5	1024.8	44.48
Accumulator	842	50,....,59	722.09,..,646.39	-
HX	50	80 90 100	468.44 408.01 363.69	23.42 20.40 18.18
Heated Components	179.3	Infinite	0	0
Unheated Components	141.23	calculated	calculated	calculated

Table 8-1: Assumed TTCS loop temperature (First safety approach)

The calculation procedure is as follows:

1. With the assumed temperatures of condensers, accumulator and the heat exchanger the local densities are calculated and the CO_2 mass in those components.
2. The total CO_2 mass in the loop is constant (743.35 grams) and thus the mass of the CO_2 in the unheated components is calculated and thus the density. From this density the maximum allowable temperature in the unheated components is calculated.

The resulting maximum allowable unheated components temperature is seen in Figure 8-1.

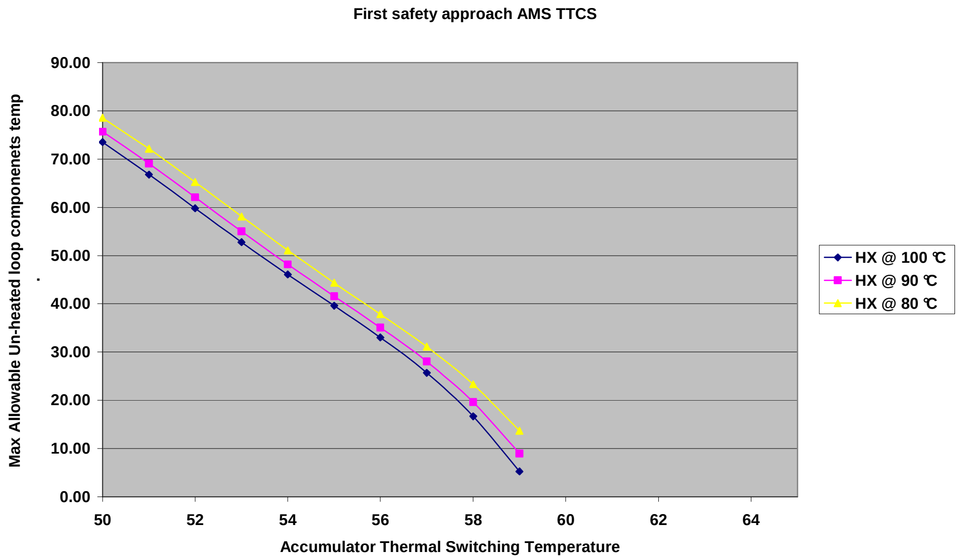


Figure 8-1: Maximum Allowable unheated loop components temperature

Changing the accumulator set point temperature has a larger effect on the max allowable temperature in the unheated components than changing the set point of the heat exchanger. This is due to the larger volume contained in the accumulator.

8.2.1 Conclusion approach 1

It can be concluded that for example if:

1. $T_{\text{accu thermostats protected}} \leq 50$ °C
2. $T_{\text{condenser thermostat protected}} \leq 5$ °C
3. $T_{\text{overheated parts}}$ < very high temperature
4. $T_{\text{heat exchanger}} < 100$ °C

And

5. The unheated loop components temperature < 75 (**to be checked by modelling**)

Then P_{TTCS} < MDP (160 Bar) ==> Design is safe

8.3 Second Approach

In this approach the following assumptions are made:

- Condensers are thermostat protected and do not exceed the temperature of -5 [°C].
- Heat exchanger is thermostat protected and can not exceed the temperatures of respectively 100 [°C].
- For the heated component the following three scenarios are assumed:
    1. All heated components have a maximum temperature of 300 °C.
    2. All heated components have a maximum temperature of 300 °C except the pumps and the evaporator which have a maximum temperature of 100 °C.
    3. All heated components have a maximum temperature of 450 °C except the pumps and the evaporator which have a maximum temperature of 100 °C.
- An accumulator temperature is assumed varying from 50 °C to 59 °C.

The maximum allowable temperature in the unheated components is calculated such that the pressure in the system, under the above described conditions, is equal to the maximum allowable design pressure of 160 [Bar].

The maximum allowable not heated components temperature is calculated and seen in Figure 8-2.

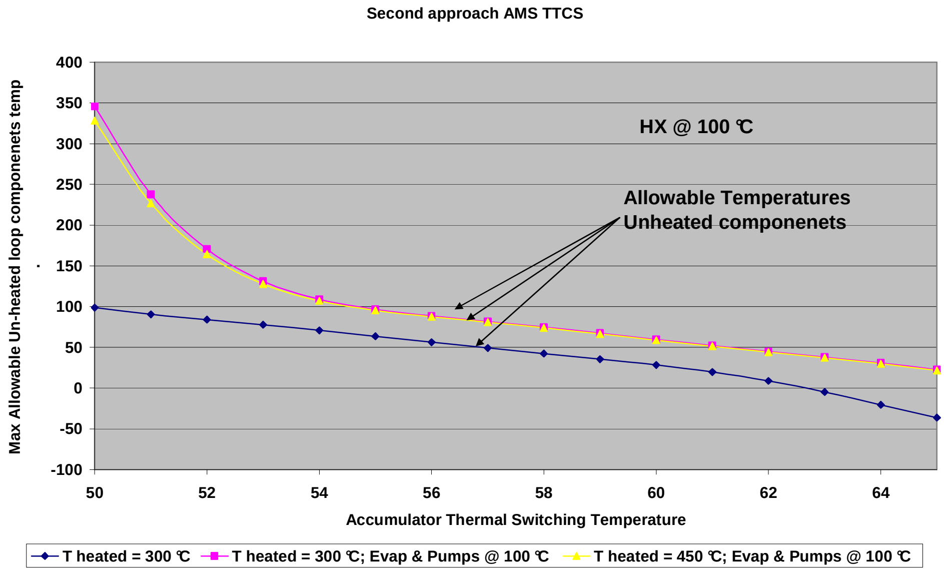


Figure 8-2: Max. Allowable Unheated loop components temp.

8.3.1 Conclusion approach 2

It is thus concluded that for example if:

1. $T_{\text{accu thermostats protected}} \leq 50$ °C
2. $T_{\text{condenser thermostat protected}} \leq 5$ °C
3. $T_{\text{overheated parts}} < 300$ °C
4. $T_{\text{Evap, pumps}} < 100$ °C
5. $T_{\text{heat exchanger}} < 100$ °C

And

6. The unheated loop components temperature < 350 (**to be checked by modelling**)

Then $P_{TTCS} <$ MDP (160 Bar) ==> Design is safe

8.4 Conclusion on safety approach

Based on the results of both approaches it is shown that the TTCS pressurised system stays below the Maximum Design Pressure of 160 bar.

In order to finalise the safety analyses some additional thermal modelling is needed (evaporator, accumulator). However the approaches show that margin is available. Therefore it is expected no additional design changes will be needed.

Appendix A: Conductivity between pre-heater and base plate

$k_{sst} := 16.5 \frac{W}{m \cdot K}$

$h_1 := 3.0mm$

$C_{sst} := 480 \frac{J}{kg \cdot K}$

$h_2 := 3.5mm$

$a := 5mm$

$b := 8mm$

$\rho_{sst} := 7800 \frac{kg}{m^2}$

$dx := 10mm$

$H_{STO} := 0mm$

$C_{cont} := 2000 \frac{W}{K \cdot m^2}$

$R_1 := \frac{h_1}{k_{sst} \cdot b \cdot dx}$ $\qquad R_1 = 2.273 \frac{K}{W}$

$R_2 := \frac{a + b}{2 \cdot k_{sst} \cdot h_2 \cdot dx}$ $\qquad R_2 = 11.255 \frac{K}{W}$

$R_{cont1} := \frac{1}{C_{cont} \cdot a \cdot dx}$ $\qquad R_{cont1} = 10 \frac{K}{W}$

$R_{STO} := \frac{H_{STO}}{k_{sst} \cdot a \cdot dx}$ $\qquad R_{STO} = 0 \frac{K}{W}$

$R_{cont2} := R_{cont1}$

$R_{tot} := R_1 + 0.5 \left(R_2 + R_{cont1} + R_{STO} + R_{cont2}\right)$

$R_{tot} = 17.9 \frac{K}{W}$

$G_{tot} := \frac{1}{R_{tot}}$ $\qquad G_{tot} = 0.056 \frac{W}{K}$

Appendix B: Conductivity between cold orbit heater copper structure and base plate

$$k_{sst} := 16.5\frac{W}{m\cdot K} \qquad k_{cu} := 390\frac{W}{m\cdot K} \qquad h_1 := 4.0mm$$

$$C_{sst} := 480\frac{J}{kg\cdot K} \qquad C_{cu} := 378\frac{J}{kg\cdot K}$$

$$a := 10mm \qquad b := 10mm \qquad D := 4.0mm$$

$$\rho_{sst} := 7800\frac{kg}{m^2} \qquad \rho_{cu} := 8960\frac{kg}{m^2}$$

$$C_{cont} := 1500\frac{W}{K\cdot m^2} \qquad H_{STO} := 0mm$$

$$R_1 := \frac{h_1}{k_{cu}\cdot\left(a\cdot b - \frac{3.14D^2}{4}\right)} \qquad R_1 = 0.117\frac{K}{W}$$

$$R_{cont1} := \frac{1}{C_{cont}\cdot\left(a\cdot b - \frac{3.14D^2}{4}\right)} \qquad R_{cont1} = 7.624\frac{K}{W}$$

$$R_{STO} := \frac{H_{STO}}{k_{sst}\cdot\left(a\cdot b - \frac{3.14D^2}{4}\right)} \qquad R_{STO} = 0\frac{K}{W}$$

$$R_{cont2} := 0$$

$$R_{tot} := R_1 + \left(R_{cont1} + R_{STO} + R_{cont2}\right)$$

$$R_{tot} = 7.742\frac{K}{W}$$

$$G_{tot} := \frac{1}{R_{tot}} \qquad G_{tot} = 0.129\frac{W}{K}$$

Appendix C: Conductivity between HX Brackets and base plate

Material Properties:

Inconel

$k_{inc} := 15.5 \frac{W}{m \cdot K}$

$C_{p\_inc} := 480 \frac{J}{kg \cdot K}$

$\rho_{inc} := 8440 \frac{kg}{m^3}$

SS

$k_{ss} := 15.3 \frac{W}{m \cdot K}$

$C_{p\_ss} := 480 \frac{J}{kg \cdot K}$

$\rho_{ss} := 7800 \frac{kg}{m^3}$

Contact Conductance :

$C_{cont} := 5000 \frac{W}{m^2 \cdot K}$

Dimensions:

$H_{StO} := 1.0mm$

$H_{BP} := 10mm$

$H_{HX} := 10mm$

$H_{BoltCyl} := 22mm$

$H_{BoltHead} := 5mm$

$D_{in} := 5mm$

$D_{out} := 9mm$

$A_{HX} := \left(D_{out}^2 - D_{in}^2\right) \cdot \frac{\pi}{4}$ $\quad A_{HX} = 43.982mm^2$

$A_{Blts} := \left(D_{in}^2\right) \cdot \frac{\pi}{4}$ $\quad A_{Blts} = 19.635mm^2$

$A_{Blts\_BP} := \pi \cdot D_{out} \cdot H_{BP}$ $\quad A_{Blts\_BP} = 282.743mm^2$

Resitances

$R_{HX} := \frac{H_{HX}}{k_{inc} \cdot A_{HX}}$ $\quad R_{HX} = 14.669 \frac{K}{W}$

$R_{cont} := \left(C_{cont} \cdot A_{HX}\right)^{-1}$ $\quad R_{cont} = 4.547 \frac{K}{W}$

$R_{StO} := \frac{H_{StO}}{k_{ss} \cdot A_{HX}}$ $\quad R_{StO} = 1.486 \frac{K}{W}$

$R_{blts} := \frac{H_{BoltCyl}}{k_{ss} \cdot A_{Blts}}$ $\quad R_{blts} = 73.232 \frac{K}{W}$

$R_{Blts\_BP} := \left(C_{cont} \cdot A_{Blts\_BP}\right)^{-1}$ $\quad R_{Blts\_BP} = 0.707 \frac{K}{W}$

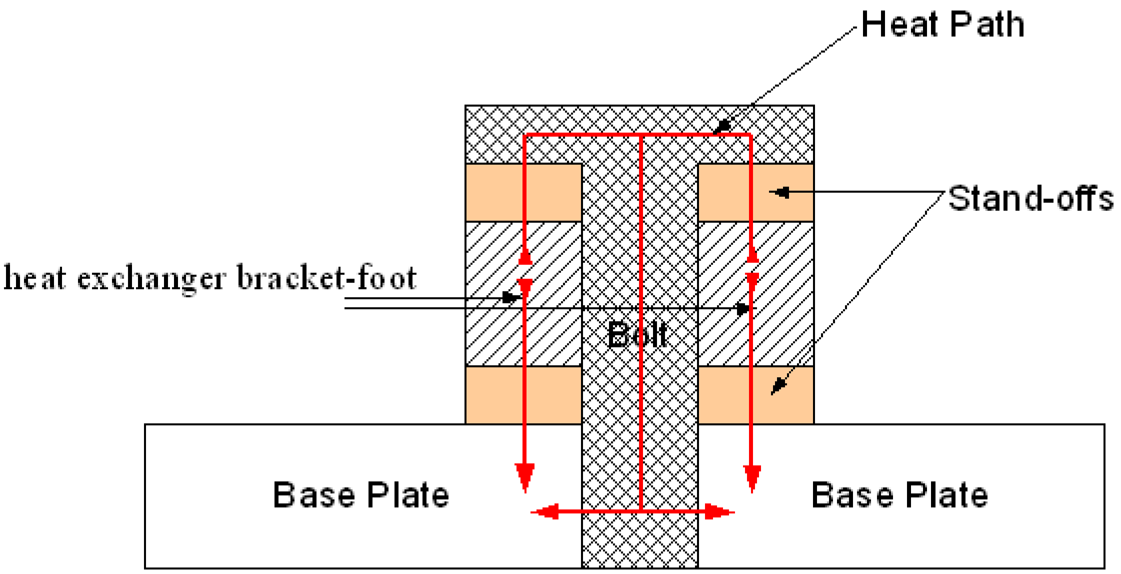
$$R1 := \frac{R_{HX}}{2} + R_{cont} + R_{StO} + R_{cont} \qquad R1 = 17.915\frac{K}{W}$$

$$R2 := R_{HX} + R_{cont} + R_{StO} + R_{cont} + R_{blts} + R_{Blts\_BP} \qquad R2 = 99.189\frac{K}{W}$$

$$G1 := \frac{1}{R1} \qquad G1 = 0.056\frac{W}{K}$$

$$G2 := \frac{1}{R2} \qquad G2 = 0.01\frac{W}{K}$$

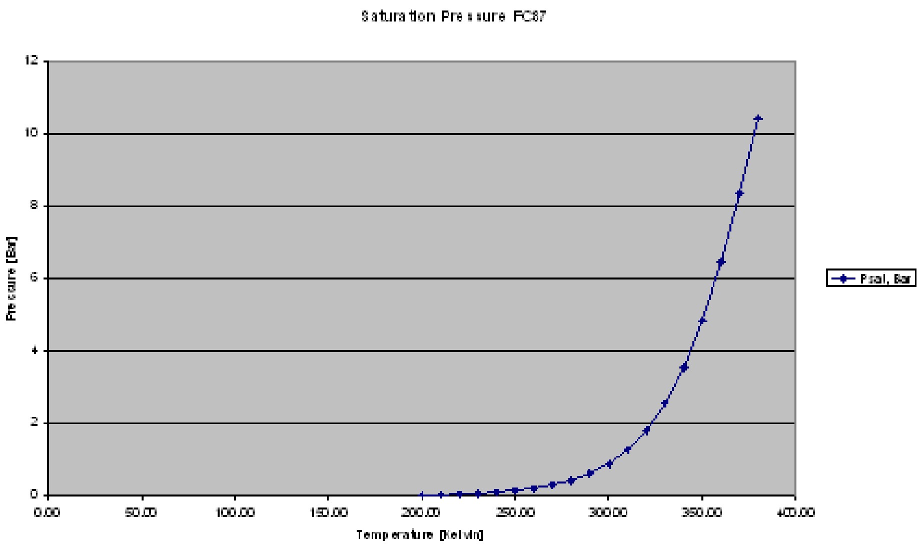
$$G_{tot\_Bolt} := 2(G1 + G2) \qquad G_{tot\_Bolt} = 0.132\frac{W}{K}$$



APPENDIX D:

OHP Stress calculation

The maximum stress in the OHP tubing is based on the maxuimum design pressure. The maximum design pressure is based on a maximum mean temperature of 373 K (=100 ℃) of the OHP.
The pressure of FC-87 (the OHP working fluid) is 5.3 bar as can be seen in below P-T diagram.



$P_{MDP} := 8.94\,10^{5}\,Pa$ Maximum Design Pressure

$t := 0.15\,mm$ OHP Pipe dimensions

$R_{in} := 0.6\,mm$

$R_{out} := R_{in} + t$ $\qquad R_{out} = 0.75mm$

$P := P_{MDP}$

$r := R_{in}$

The maximum stresses in the material can then be calculated by:

<u>For small tube wall thicknesses</u>

$\sigma_t := P \cdot \frac{R_{in}}{t}$ $\qquad \sigma_r := P_{MDP}$ $\qquad \sigma_r = 8.94\times 10^{5}\ Pa$ Radial stress

$\sigma_t = 3.576\times 10^{6}\ Pa$ Tangential stress

For large wall thicknesses the largest stress at the inner wall is:

$$\sigma_r := P \cdot \frac{R_{in}^2}{R_{out}^2 - R_{in}^2} \cdot \left(1 - \frac{R_{out}^2}{r^2}\right)$$

$\sigma_r = -8.94 \times 10^5 \text{ Pa}$ Radial stress

$$\sigma_t := P \cdot \frac{R_{in}^2}{R_{out}^2 - R_{in}^2} \cdot \left(1 + \frac{R_{out}^2}{r^2}\right)$$

$\sigma_t = 4.073 \times 10^6 \text{ Pa}$ Tangential stress

As limiting stress the Von Mises stress can be taken:

$$\sigma_{VM} := \sqrt{\sigma_r^2 + \sigma_t^2 - 2 \cdot \sigma_r \cdot \sigma_t}$$

$$\sigma_{VM} = 4.967 \times 10^6 \text{ Pa}$$

With a safety factor, the material should have a yield stress larger than:

$SF := 4$ SF is the safety factor

$\sigma_{yieldlimit} := SF \cdot \sigma_{VM}$ $\sigma_{yieldlimit} = 1.987 \times 10^7 \text{ Pa}$

$\sigma_{yieldlimit} = 19.867\text{MPa}$

Above calculation shows that all materials with a yield stress above the yield limit can be used:

The tube material for the OHP is stainless steel with a minimum yield stress of 195 MPa. Therefore
all stresses in the material will be acceptable.

Common stainless steels have yield strength around 200 MPa and higher

316 L stainless steel has a yield strength of 234 MPa (source Perry chemicals engineers handbook sixth edition table 23-10 p23-43) and easily fulfils the yield stress limit.